Human performance in space telerobotic manipulation

Philip R. Lamb

University of Canterbury

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Psychology at the University of Canterbury

Supervised by Dr Dean H. Owen

2002

Acknowledgments

I offer my appreciation and thanks to all those who participated in and contributed towards the success of this research. In particular, I would like to thank Dr Dean Owen for both inspiring me to pursue study in the field of Human Factors and for acting as a mentor and advocate for ideas relating to the present research.

I would also like to acknowledge the financial support provided by a University of Canterbury Research Award. I also acknowledge those who assisted at various stages in the development of the simulator, particularly Gino van den Bergen, and Troy Dawson and the OpenGL engineering team at Apple Computer, who provided portions of the code.

Most importantly, thanks to my family and friends for their tireless encouragement, financial support and patience especially during my long periods of absence throughout the months of laboratory work.

Contents

List of figures

List of tables

Abstract

An experiment was conducted to evaluate the potential for improved operator performance in a space-based telerobotic manipulation task when the operator's control interface was based around an egocentric rather than exocentric frame of reference (FOR). Participants performed three tasks of increasing difficulty using a virtual reality-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. Increased head movement and higher number of errors in arm motion indicated that the mobile viewpoint suffered from confounding uncontrolled keyhole effects. No correlation between performance and prior 3D simulation experience was observed. There was a significant effect of gender on performance in line with results from the field. The requirement for telemanipulation interfaces to represent critical kinematic limitations in the interface emerges in discussion of origins of performance differences between conditions. The results provide support for the partial application of an egocentric telepresence control interface to space-based articulated manipulators. Different factorings of ego- and exocentric FORs in order to alleviate poor performance under the mobile viewpoint are discussed along with implications for other space-based telemanipulation applications and fruitful approaches to further studies.

1 Introduction

1.1 Robotic manipulation tasks in space

Freed from the usual constraint imposed by gravity, bodies in space may adopt any orientation with respect to each other without internal disturbance. However, in the case of manipulation tasks in space, the orientation of bodies with respect to each other is of prime importance. Manipulation and assembly of complex and large-scale structures under zero-gravity conditions outside Earth's atmosphere are essential elements in ongoing progress in human exploration and colonisation of space.

Remote manipulator systems (RMS) have been an essential enabler of space manipulation and assembly operations. The best known, most successful, and most extensively studied application of a spaceborne RMS is the space shuttle RMS (SRMS), known colloquially as “Canadarm”. The SRMS has been used extensively throughout the 18-year history of the space shuttle program, successfully performing a large variety of manipulation tasks, and has been the subject of a program of ongoing study, upgrades and human-in-the-loop evaluation both within NASA and other research institutes (Nguyen & Hughes, 1994). (An overview of the SRMS system appears in Appendix A.)

However, despite the application of remote manipulator systems and other engineering techniques designed to simplify space-based assembly operations, such as use of prefabrication, modularity, and automated deployment, assembly tasks still require substantial extra-vehicular activity (EVA) by spacewalking astronauts to complete. The seemingly routine nature of travel into space does little to remind us of the extreme hostility of that environment and just how fragile and poor a replica of the terrestrial ecology the “bubble” of the space vehicle and space suit actually are, and EVA is costly, dangerous, and requires highly trained personnel. In the construction of the International Space Station, a new remote manipulator system, the SSRMS, has been deployed and others are planned to substitute further for some of the requirements for EVA in space manipulation tasks, and thus reduce cost, increase efficiency, and allow a broader range of skilled personnel into space (Ruoff, 1994).

1.2 The changing nature of remote manipulation tasks in space

Hitherto, the SRMS has provided the overwhelming majority of proven knowledge in the field of space robotics. However, the established paradigms for control of space manipulators are less well proven in the domain of multi-body assembly tasks, such as the ongoing construction of the International Space Station. Indeed, use of the SRMS in multi-body assembly tasks and the advent of the SSRMS represent the beginning of a new epoch in the tasks to which telerobotic manipulation is being applied, with a drastic increase in the complexity of manipulation operations.

Previously, the SRMS performed tasks involving only the shuttle and a single external body, and could naturally adopt the body of the space shuttle as a fixed plane of reference. However, in multi-body assembly tasks, there is frequently no natural plane of reference. Tasks may involve multiple external bodies, none of which will necessarily have a predetermined orientation relative to the shuttle or any other part of the space station.

Additionally, the SRMS operators rely on a mix of line-of-sight operation out spacecraft windows, closed-circuit camera views, and verbal information relayed from EVA astronauts, whereas in multi-body assembly tasks using the SRMS there is unlikely to be a line-of-sight to the manipulator workspace, and in the case of the SSRMS there is no line-of-sight, operators relying solely on camera views and information relayed from EVA astronauts.

The SRMS *manual* control interface remains functionally unchanged since its 1970s design. In part, this is owes to parsimony: the SRMS has proved effective in the tasks it was originally designed to do. The SRMS and SSRMS control interfaces are both based around resolved motion rate control (Whitney, 1969), which is designed to exploit alignment in orientation of the control coordinate system (the axes in which the operator expresses control actions) and the task-space coordinate system (the axes in which the end-effector moves). Such an alignment is known in human control terms as *direct correspondence*. The astronaut views the manipulator workspace from the aft flight deck, a fixed position relative to the shoulder of the arm. Control commands for motion of the SRMS end-effector are interpreted relative to the axes of the body of the space shuttle. Thus, when the astronaut is able to view the SRMS manipulator workspace out of the shuttle windows, there is direct correspondence between his or her control movements and the resultant visual motion of the end-effector.

However, in using the SRMS and SSRMS in multi-body assembly tasks, direct correspondence is the exception rather than the rule. There is a body of research that indicates a decline in performance and an increase in error rate when direct correspondence is violated.

In studying the coordination between control actions and their displayed effects in a remote manipulation task, Smith and Stuart (1993) varied the position and orientation of the camera in the pick-and-place style task using a master-slave telerobot and concluded that left-right reversal and up-down reversal both caused major performance impairments, as measured by time to complete the task. Similar results emerge from other fields. Holden, Flach and Donchin (1999) studied coordination between movements of a surgeon and a camera manipulated by the surgeon in a simulated laparoscopic surgical task. They found that changes to either the camera orientation or the surgeon's orientation disrupted performance in the pick-and-place task. However, when the position of camera and surgeon changed together, skilled performance was maintained. They suggested that skill in such remote manipulation tasks depends on consistent mapping between the virtual hands and eyes, but not on the particular visual or motor orientations.

Results such as this call into question the utility of the established SRMS operator-manipulator interface. The degree of performance decrement caused by violation of principles of direct correspondence in the SRMS and SSRMS remain unclear, especially since these systems remain relatively untested in multi-body assembly tasks. However what is clear is that such tasks require a great deal of costly training in their preparation, significant ground-based and EVA support resources during their execution, and remain highly awkward for even the most capable operator.

The question is posed then as to what might be done to improve the interface to enable operators to perform remote manipulation tasks for multi-body assembly to the same standard as previous, simpler manipulation tasks. Important dimensions of operator performance include executing desired procedures with minimum time to completion, maximum positioning precision, minimising control effort to reduce expenditure of control-related resources (electrical power, reaction system propellant) and most importantly, avoidance of situations that set the occasion for errors which have potential to compromise the safety of crew or the integrity of the spacecraft, such as collisions between manipulated objects and spacecraft.

1.3 Approaches to the operator-manipulator interface problem

There have been a number of academic and engineering approaches taken towards the operator-manipulator interface problem posed by multi-body assembly tasks. Some of these have sought to compensate for the poor human-machine interface by substituting more automation in place of the human operator. However, application of a total-automation strategy to telerobotic manipulation tasks in space is neither practical nor generally feasible. In the complex sociotechnical system of space exploration, operation is frequently at the limit of known practice, and thus human skill and problem solving form a critical component of the system. Additionally, the dynamic nature of the system is such that it frequently lacks the predictability required for high levels of automation. Thus, the focus here is instead on approaches that offer promise for the improvement of the human-machine interface.

One major approach to overcoming the limitations of traditional human-machine interfaces has been to apply the use of virtual reality technology to the interface. Applications of this approach build “virtual environments” which the human operator explores and interacts with, using now-familiar virtual reality technology such as computer-rendered graphics, head-mounted displays, position trackers, and tactile input devices (Carr & England, 1995). Early advocates of virtual reality technology (e.g. Rheingold, 1991) hoped that in such an approach the human operator would experience a sense of immersion within the given data representation. In cases where the physical layout of a remote location was represented, it was predicted that such an immersion would lead to a sense of *telepresence* (Minsky, 1979, September), that the operator would experience a sensation of being physically present at the remote location.

This prediction has been the implicit motivation for much of the virtual environment research originating from the engineering disciplines (Sheridan, 1992). Yet, Lumelsky (1991) raises a number of practical objections to such an approach. Lumelsky observed that many of the systems actually built had low overall efficiency and awkward interaction between the operator and the machine. He also observed that the teams testing such systems preferred to have the manipulator controls located very close to the master, seemingly contradicting the researchers’ claims that these systems provided a suitable platform for teleoperation. In two experiments, he demonstrated superior performance of a motion-planning algorithm over a human operator in a simple two-dimensional motion-planning task. Lumelsky proposed that telepresence interfaces were not supporting their claims, but were rather engaging the operator in continuous and demanding real-time control, despite the operator being ill equipped to perform such control. Lumelsky hypothesised that human operators lack the ability to deal with the task of motion planning of a robot arm, even in a relatively uncluttered environment, and that such a task should be left to automation.

Lumelsky's proposed approach, and indeed most previous research in the human factors of telemanipulation performance, has taken the perspective that in a conditionally-stable system involving both automated control and a human operator, unpredictability and unreliability in the system is attributable to flaws in the performance of the human element. Seeking unconditional stability for the entire system, such approaches treat the human element simply as a subsystem of the larger system (Flach, 1990a) and attempt to identify and model the weaknesses of human element in systems engineering terms so that these may be replaced by automatic control. These approaches propose automation in order to reduce the unpredictability and unreliability of the system.

An alternative strategy, motivated by an ecological approach to human factors (Flach, 1990b; Vicente, 1995) is to consider the both the task and the tools available for interacting with the task as an embedding environment for the human actor, and to take the combined actor-environment system as the unit of analysis. This *ecological* approach recasts the problem, from one of identifying the weaknesses of the human element of the system, to one of discovering the critical sources of information that enable skilled human performance and identifying when these sources of information change, become unavailable, or become unspecific to the aspect of the system under control (Owen, 1990). The ultimate aim of the ecological approach is to reduce the effort of information acquisition and control action from the operator to such a trivial level that the operator is freed from the requirement of continuous control and is able to adopt a supervisory role. This ecological approach to supervisory control is perhaps closer to the original intention of those who conceived the term

(Sheridan, 1994). In this conception, the role of the human does not just *change* from direct operation to planning and evaluating operations of lower-level automation, but rather these activities – planning and evaluating – *emerge naturally* as a consequence of reduced operator workload.

1.4 Application of an ecological approach

In the case of the astronaut operator performing telerobotic manipulations using the SRMS, there has to date been little research identifying the critical sources of information that enable skilled performance. Yet, knowledge of these sources is both an essential first step in designing any automated system and essential in deciding how best to make sure these sources of information remain available to the astronaut operator in the more challenging environment of multi-body assembly and manipulation tasks.

Reaching for, grasping, and manipulating objects in the environment is an activity fundamental to most human action. However, reaching, grasping, and manipulation tasks performed telerobotically in space with the SRMS are very difficult, requiring extensive training and costly support both from the ground and from EVA personnel. Therefore, there is a poor match between the astronaut operator's natural skill in these activities and the support provided by the SRMS control interface for expressing control actions in the same terms. For the astronaut engaged in a telerobotic manipulation task in space, the perception-action interface with the environment is at variance in a number of ways with the perception-action interface typically experienced when engaged in a direct manipulation task on earth using the hands.

In any remote manipulation task, displays, controls, and the remote manipulator itself become an extension of the actor's ego (Sheridan, 1994). Although the SRMS display and control systems provide information to the astronaut about the environment, this information is mediated and transformed by properties of the cameras and monitors. Extra information may be available too, through sensors such as temperature gauges, warning lights and the like. Similarly, the astronauts control actions are mediated and transformed by properties of the control hardware, software, and actuators.

Additionally, the zero-gravity space environment creates conditions that are not typically experienced on earth. Some sources of information are unavailable, for example information from surface interactions or collisions that are usually conveyed by sound. Other information becomes informative about a different aspect of the environment than is usual for the astronaut when normally resident on earth. For example, straight-line motion of a body in space has different physical meaning to the same straight-line motion on earth, owing to the different dynamics of zero-gravity.

Thus, in order to successfully perform remote manipulation tasks with the present SRMS, there are a number of new potentially informative sources which an inexperienced operator must become attuned to and a number of old potentially uninformative sources to learn to ignore. Yet requiring suppression of natural perception-action skill in activities so fundamental as reaching for, grasping and manipulating objects, constitutes a significant barrier to acquisition of skill with the SRMS and the successful performance of telerobotic manipulation tasks in space.

1.5 Overcoming complex spatial relationships

At the heart of the variance between the SRMS control interface and the everyday environment in the affordance of reaching, grasping and manipulating is the spatial relationship between the human operator and the manipulator. The results from Smith and

Stuart (1993) indicate that there must be spatial coordination between the operator's control actions and their viewed effect. As suggested by Holden, Flach and Donchin (1999), changes in camera view must be accompanied by a coordinated change in control axis.

In the present SRMS deployed on the Space Shuttle, although the SRMS operator is able to select between several different camera views, the control frame of reference is not linked to the selected camera view because this would produce a number of inconsistencies. For example, if the operator were making control actions to the arm to move the end-effector in a straight line, and while doing so switched to a different camera perspective, the control positions the operator was holding at the time of the switch would be referenced to the new frame provided by the new camera perspective. The direction of end-effector motion would thus change at the time of the camera switch. Linking control frame of reference and camera view in this way is thus undesirable.

One potential solution to this problem is to link not only control frame of reference to changes in viewpoint, but also the reverse: to link movement of the viewpoint to control action itself. In the case of the SRMS, this would suggest that the operator's viewpoint should be fixed to and move with the manipulator arm. In this way, the operator's control actions would change both the viewpoint and the control frame of reference in a coordinated manner.

Whereas at present in the SRMS, the operator's physical space must be adjacent to the manipulator arm's physical space, the use of virtual reality technology to create a virtual environment allows the operator's physical space to be arbitrarily located. At present, the operator is informed about the state of the manipulator's physical environment via viewing directly through the windows, via closed circuit television (CCTV), and via sensor displays (Figure 1). Recreating this situation in a virtual environment, the operator's line of sight is no longer available, and the operator is informed via CCTV and sensor displays only. The manipulator space, thus viewed, is *real* in the sense that it is a true representation of the manipulator environment. It is however *virtual* in the sense that the information on which the astronaut acts is mediated and transformed by the computerised head-mounted display.

It is clear that with the creation of a virtual manipulator space, the spatial relationship between the operator's physical space and the manipulator's virtual space may be selected arbitrarily. There are a number of potentially useful configurations of this relationship. Of particular interest are the *exocentric* case in which the manipulator virtual space is viewed from a fixed external location, and the *egocentric* case in which the manipulator virtual space is collocated with the operator's physical space. [See McCormick, Wickens, Banks, & Yeh (1998) for a fuller discussion of exo- and ego-centric frames of reference.]

In the exocentric configuration, the participant views the SRMS workspace from a fixed position with respect to the shoulder of the arm. Head movements within a normal range for a seated person allow a small degree of movement about the fixed viewpoint. To draw a parallel to the present-day situation aboard the shuttle, the exocentric case is analogous to a situation in which the SRMS operator is seated at a control station on the aft flight deck and is viewing the manipulator workspace through the payload bay windows.

In the egocentric configuration, the participant views the SRMS workspace from a mobile position tethered to the manipulator end-effector. Again, head movements within a normal range for a seated person allow a small degree of movement about this tethered position. To draw a parallel to the present-day situation aboard the shuttle, this is loosely analogous to a situation in which the SRMS operator is seated at a control station on the aft flight deck and is viewing the manipulator workspace through the camera mounted on the manipulator end-effector.

An exocentric virtual environment preserves the present-day real-life spatial relationship between the operator and the manipulator. 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, control translations and rotations would cause an equal and opposite change in the position and orientation of the manipulator virtual environment relative to the operator. It is hypothesised however that the net phenomenal experience of the operator would not be motion of the virtual environment about him or her, but that he or she is in fact translating and rotating through a fixed and stable environment.

Thus, whereas an exocentric virtual environment would create a situation in which the SRMS control task is analogous to a reaching and grasping task performed with the hands, an egocentric virtual environment may effectively change the analogous task to control of self-motion.

In a sense, the empirical investigation of the utility of different spatial relationships between operator and task is a generalisation to three dimensions of the results from studies of control-display compatibility in two dimensions.

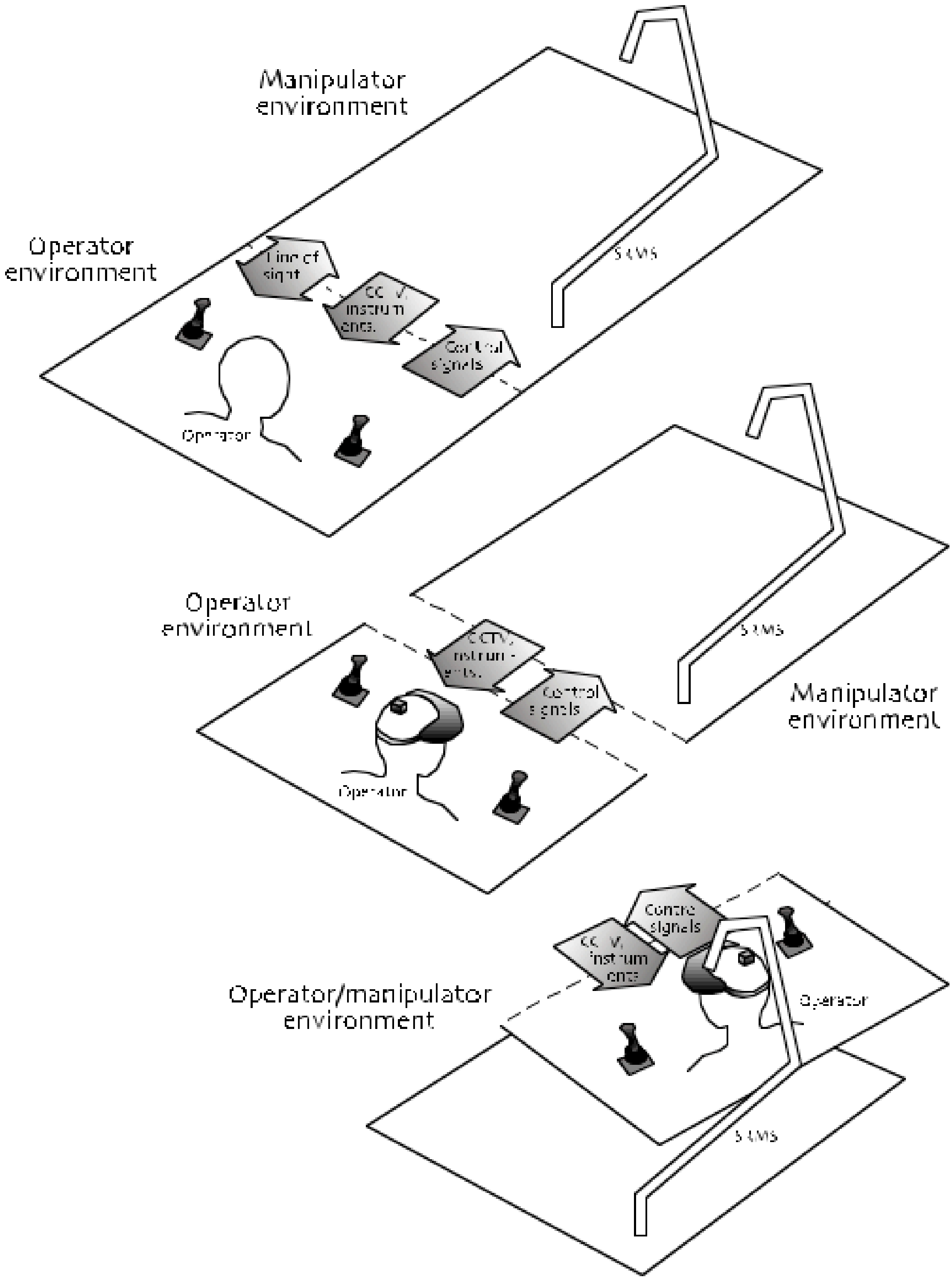


Figure 1. Relationship between operator and work environment. In the actual space shuttle (top), the operator is informed about the state of the manipulator environment via windows, CCTV, and sensors. In the exocentric virtual environment (middle), this information is mediated by a head-mounted display, but the spatial relationship between operator and manipulator is preserved. In the egocentric virtual environment (bottom), the operator environment is collocated with the manipulator environment.

1.6 Experimental approach

The aim of the present research was to determine the effects of varying certain aspects of the human interface to a telerobot on the performance of the human operator using the robot to perform a manipulation task under zero-gravity conditions in a space environment. The particular telerobot considered was the space shuttle robotic manipulation system (SRMS).

To investigate this empirically, 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 hypothesised 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 simulation was designed to replicate a space-borne work domain similar to the space shuttle RMS. The simulation, implemented using virtual reality technology, provided both exocentric and egocentric operator environments and a representative set of zero-gravity robotic manipulation tasks. The simulation served as a platform for empirical evaluation of the research question and for additional investigation of other human factors and cognitive ergonomics issues that arise in the application of a telepresence system to zero-gravity robotic manipulation tasks in a space-borne work domain including, but not limited to, simulator sickness effects.

The overarching aim was to draw conclusions with respect to understanding human performance in teleoperation, theories of telepresence, the design of interfaces to telerobotic systems, and understanding human perception and action in manipulation tasks of high spatial complexity.

1.7 Independent variables

As the purely exocentric and purely egocentric operator environments differed in more than one dimension, and as each was potentially of different utility for different manipulation tasks, experimental comparison of operator performance in each environment was broken down into three independent variables. These were evaluated in a factorial experimental design:

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 moved 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. level ground), (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 combinations of experimental factors (1) viewpoint frame of reference and (2) control frame of reference created four distinct experimental conditions, as indicated in Table 1.

Table 1. Names of Experimental Conditions.

		Factor (1) Viewpoint frame of reference:	
		Fixed near SRMS shoulder.	Mobile attached near end-effector.
Factor (2) Control frame of reference:	Aligned with body of space shuttle.	Fixed, world-referenced.	Mobile, world-referenced.
	Aligned with arm end-effector.	Fixed, self-referenced.	Mobile, self-referenced.

2 Method

2.1 Participants

45 participants were recruited from the student population at the University of Canterbury, 35 males and 10 females. Ages ranged between 17 and 36 years, with a median age of 20.

It was expected that a small proportion of participants would find the task prohibitively difficult due to its demanding requirements on motor skill and spatial perception/action coordination. It was also expected that some participants might be susceptible to simulator sickness effects to a degree that would preclude them from completing the session. The experimental session was structured so that participants who fell into these categories could be objectively identified during the initial training phase of the experiment and could be withdrawn from the experiment at the completion of the training phase, without undue offence or disappointment to the participant. (In the event, no participants were withdrawn at the juncture of training and testing, however 6 participants withdrew at various stages during the test phase owing to the onset of intolerable simulator sickness effects. The data of one further participant was withdrawn after completion of the experiment due to a malfunction in the automatic data recording during the experiment.)

As compensation for the time involved in participating in the study, participants were paid $10. Participation complied with requirements of the University of Canterbury Human Ethics Committee.

2.2 Materials and apparatus

2.2.1 Interactive simulator

To provide a test bed for different control and display configurations, an interactive simulation of an SRMS control station and workspace was developed by the experimenter. A schematic of the equipment implementing the simulation appears in Figure 2.

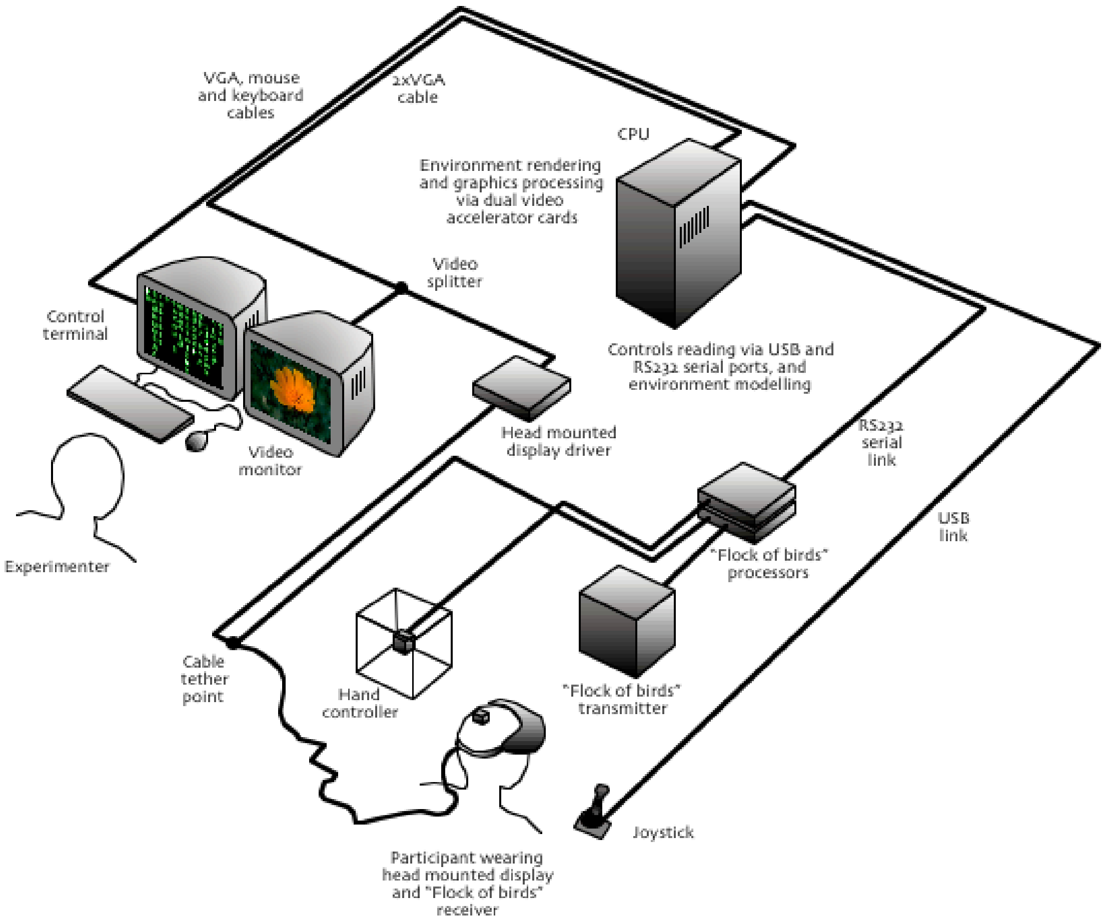


Figure 2. Schematic of equipment used in implementing the simulation.

A three-dimensional image of the simulated environment was presented to the participant through a tethered stereoscopic head-mounted display (HMD.) The HMD was a Virtual Research Systems model V8, and contained two 3.3cm 640x480 pixel active-matrix full-colour liquid crystal display elements mated with optics to produce an image focused at optical infinity. The image presented occupied a 60° field-of-view diagonally and had 100% stereo overlap. The refresh rate of the displays was 60 Hz.

A six-degree-of-freedom tethered Ascension Corporation “Flock of Birds” system tracked the position and orientation of the participant’s head in the actual environment. Position and orientation information was read from the head tracker at a rate varying between a minimum of 60 and a maximum of 100 samples per second, depending on the computer CPU load.

The participant issued position and orientation control actions through two displacement hand controllers. The left-hand controller, used for positional input, employed a second Flock of Birds six-degree-of-freedom tracker together with a supporting piece of equipment constructed by the experimenter, consisting of a enclosing cradle for the sensor suspended in the centre of an open cubic lattice of 30 cm each side, with a centre-return force provided by elastic bands. The controller is shown in Figure 3. The participant grasped the cradle and could independently apply a displacement by pushing or pulling it forwards, backwards, up, down, left or right. When released, the cradle returned to the central resting position. Only the displacement of the sensor from its resting position was read. (The orientation of the sensor, although available, was not used.) The hand controller’s tracker was connected to the computer via the same serial I/O channel used for the head tracker.

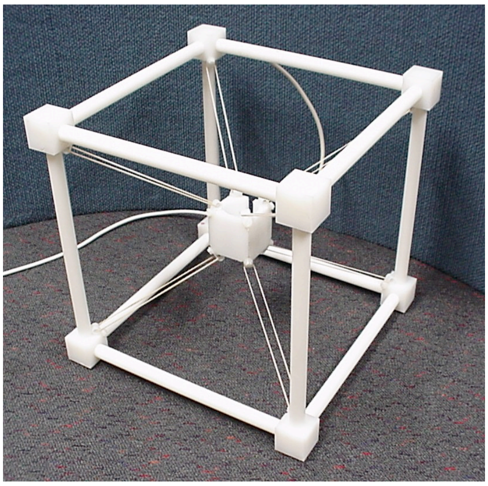


Figure 3. Oblique view of left-hand controller

The right-hand controller was an off-the-shelf three-degree-of-freedom joystick, Logitech Corporation model Wingman Extreme Digital 3D. It provided three rotational degrees of freedom: forwards-backwards, left-right, and a twist movement about the axis of the stick.

These movements corresponded to pitch, roll and yaw commands respectively. When released, springs provided a restoring force returning the stick to the resting position. The joystick connected to the computer through a Universal Serial Bus (USB) connection.

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. The participant's console is shown in Figure 4.

Figure 4. Simulator equipment located at the participant's console

The virtual environment was modelled using software written in C. A data flow diagram representation (Pressman, 2001) of the modelling software appears in Appendix C. The modelling software performed a range of tasks including processing of participant control inputs, processing of head position and orientation, calculation of arm inverse kinematics, task initiation, virtual object collision determination and dynamics, monitoring for task completion or termination, and participant virtual viewpoint determination.

The virtual environment was rendered using software written in C, which issued commands to a standard hardware-accelerated OpenGL 1.2 applications programming interface (API). A data flow diagram representation of the rendering software also appears in Appendix C. Tasks performed by the rendering software included storage of graphics models and textures, creation of OpenGL graphics primitives from virtual environment object positions, and rendering of graphics primitives from the participant's virtual viewpoint.

Two consumer-level ATi Corporation Rage 128 graphics cards provided graphics acceleration and display. Each card's VGA output was split, with one output driving one eye of the head-mounted stereo display and the other output available for the experimenter to view on a monitor.

The software was compiled for the Mac OS X operating system and ran on a single-processor PowerPC G4-based central processing unit (CPU). Modelling and rendering operations ran consecutively each frame in one process, and I/O operations and coordination of the initiation and termination of each trial ran in separate processes. An average frame rate of 75 full-stereo frames per second (FPS) was obtained, with the minimum frame rate greater than 60 FPS even during heavy computational loading from the modelling operations. This figure is well above minimum recommended 10 FPS suggested by Liu et al. (1993).

2.2.2 Simulated environment

The virtual environment was designed to replicate the salient features of the SRMS and its workspace. It consisted of correct-scale three-dimensional models of the space shuttle exterior, payload bay and manipulator arm, a visual control aid, a payload, and the backdrop.

The space shuttle exterior, payload bay and manipulator arm were all modelled as non-intersectable solids. In the case of a collision between any of the elements, a brief auditory warning was sounded, further arm motion was suspended, and then the arm backtracked for 3 s along the path taken 1.5 s immediately prior to the collision. A further beeping tone sounded during the backtracking manoeuvre.

The manipulator arm itself was a kinematically correct model of the actual SRMS. The main difference from the real SRMS was that it did not conform to joint-rate limits and the end-effector was able to move at a maximum translational rate of 1.5 m/s and a maximum rotational rate of 45 °/s, laden or unladen. (The maximum laden and unladen translational rates of the actual RMS, 0.06 m/s and 0.6 m/s respectively, were found to be too slow to allow a reasonable number of arm movements to be performed in the time available for conduction of experiment.) Dynamic properties of the arm (joint backlash, flexibility and hysteresis, and boom elasticity) were also neglected. Notwithstanding, the arm could be manoeuvred both to the edge of its reach envelope, to its joint limits, and into configurations where one or more joints approached singularity. In case of entry into one of these forbidden configurations, a different brief auditory warning was sounded, further arm motion was suspended, and then the arm backtracked for 3 s along the path taken 1.5 s immediately prior to the entry of the forbidden arm configuration. A further beeping tone sounded during the backtracking manoeuvre.

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 visual aid consisted of three lines arranged in a right-hand coordinate system and originating from the point of resolution (POR) upon and about which the controls acted. The lines were colour-coded red for the left-right / pitch axis, green for the up-down / yaw axis, and blue for the fore-aft / roll axis. The lines were 3 m in length in the virtual environment. This aid was included after a pilot experiment indicated that untrained participants had considerable difficulty understanding the effect on the controls of changing between the different control frames-of-reference. With the aid, participants could be trained to a level where they could adequately predict end-effector motion within the 15-20 minutes available for training.

The payload itself consisted of a model of a satellite, made up of a gold-textured cylinder, 3.5 m long and 1.5 m in diameter. A raised plate of the same dimensions as the end face of the manipulator end-effector was mounted in the centre of one of the end faces of the payload. It was to this plate that the end-effector was to be brought and aligned. The desired target position of the payload, which remained static during across all trials, was indicated to the participant by a semi-transparent replica of the payload model.

The backdrop consisted of an authentic Earth model that the shuttle orbited once every 56 min, and an overhead Sun that provided directional illumination. As well as adding some visual realism, the backdrop helped partially alleviate the unwanted HMD "keyhole" effect where a participant wearing a HMD has difficulty locating the imagery of interest against a uniform black background. However, in order to prevent the backdrop being used as a reference plane for the manipulation tasks, the shuttle also rotated on its longitudinal axis at a rate of 1 deg/s. This was the fastest rate that did not distract from the main visual material and was determined by a trial and error process.

All imagery was displayed in stereo, shaded, and textured to reduce depth ambiguities. The stereo imagery was produced using an asymmetrical viewing frustum, with the centreline of the two eyes converging at a distance of 15 m. The eye separation selected was 8 cm. An example of the imagery produced by the simulator appears in Figure 5.

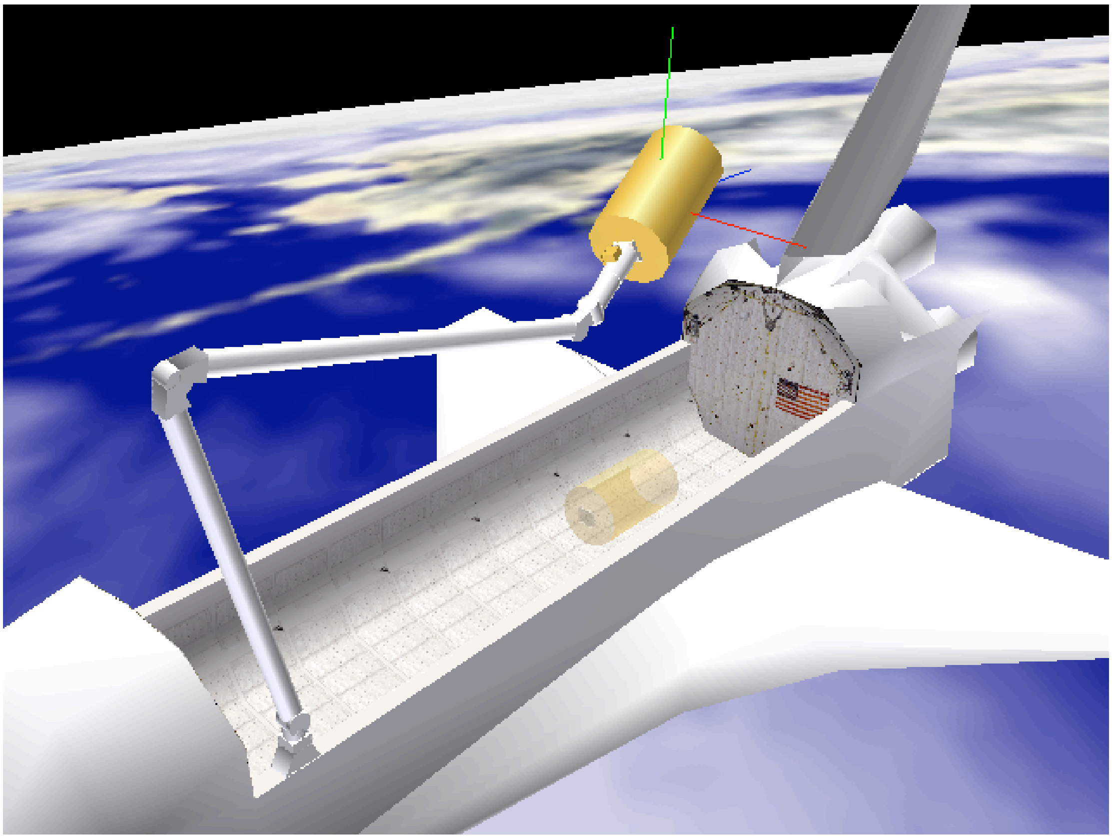


Figure 5. Example simulator imagery showing an overview of the virtual environment during a payload manoeuvre.

2.2.3 Manipulation tasks

Each manipulation task in the experiment was essentially a three-dimensional pick-and-place task. The unloaded manipulator arm began from a rest configuration aligned with and just above the port-side longeron. Participants were required to move the manipulator end-effector from its initial location and orientation to bring it to and aligned it with the payload grapple fixture. At that point, the payload became automatically latched to the arm, an audio message confirming the latch was played, and the arm was loaded. Participants were then required to move the loaded arm so as to overlay the payload on top of the translucent payload target. At all times, collisions between any parts of the arm, the payload and the shuttle body were to be avoided, and movement of the arm to place it in a forbidden configuration were also to be avoided. Participants were instructed during the training phase to deliberately make collision and forbidden-configuration errors so that they would know what to expect in case of error during the testing phase.

Although visual fidelity between the SRMS simulation and the actual Space Shuttle was desirable, the same did not apply to the task requirements of typical on-orbit SRMS operations, since most of these were considered peripheral or irrelevant to this study and were therefore neglected. Neglected SRMS task requirements included manoeuvring the shuttle so as to place a free-flying satellite to be grappled within the reach envelope of the RMS, opening of payload bay doors, release and swing-out of the SRMS from its stowed position, illumination of the payload bay, and powering up of the SRMS and control console, and selection of the correct SRMS operating mode. In the manipulation tasks in the experiment, it was implicit that the shuttle was on orbit and at the correct altitude, velocity and attitude with respect to any free-flying satellite payload to be grappled. A final neglected aspect of typical on-orbit RMS operations was management of payload systems and subsystems. For the purposes of this experiment, the payload was treated as an inert mass.

The training phase of the experiment (see § 2.3 below) presented one distinct manipulation task, then participants encountered a further three distinct manipulation tasks during the test phase. Each task was differentiated by a different initial payload position, with the initial resting position of the manipulator arm and the position of the final payload target remaining the same throughout the experiment. Each task therefore had a different level of difficulty due to the difference in complexity of the motion of required to move the manipulator arm from its resting position to the payload position and the laden arm to the payload target. The tasks were presented in order of increasing difficulty. (Although the difficulty can only be determined posteriori by an appropriate comparison of participant performance between tasks, the difficulties were ordered based on the findings of the pilot study.)

The initial payload positions for each task are displayed in Figure 6. Task T was used only in the training phase of the experiment. Tasks 1-3 were used only in the test phase.

T. The initial payload position was directly above the target, rotated 45° about its vertical axis.

1. The payload was located forward and above the target off the port wing leading edge, rotated 45° about its vertical axis.

2. The payload was located near the payload bay centreline and above the forward bulkhead, rotated 90° about its horizontal axis.

3. The payload was located off the starboard wing just aft of the forward bulkhead, and rotated 135° about its vertical axis and titled downwards approximately 30°.

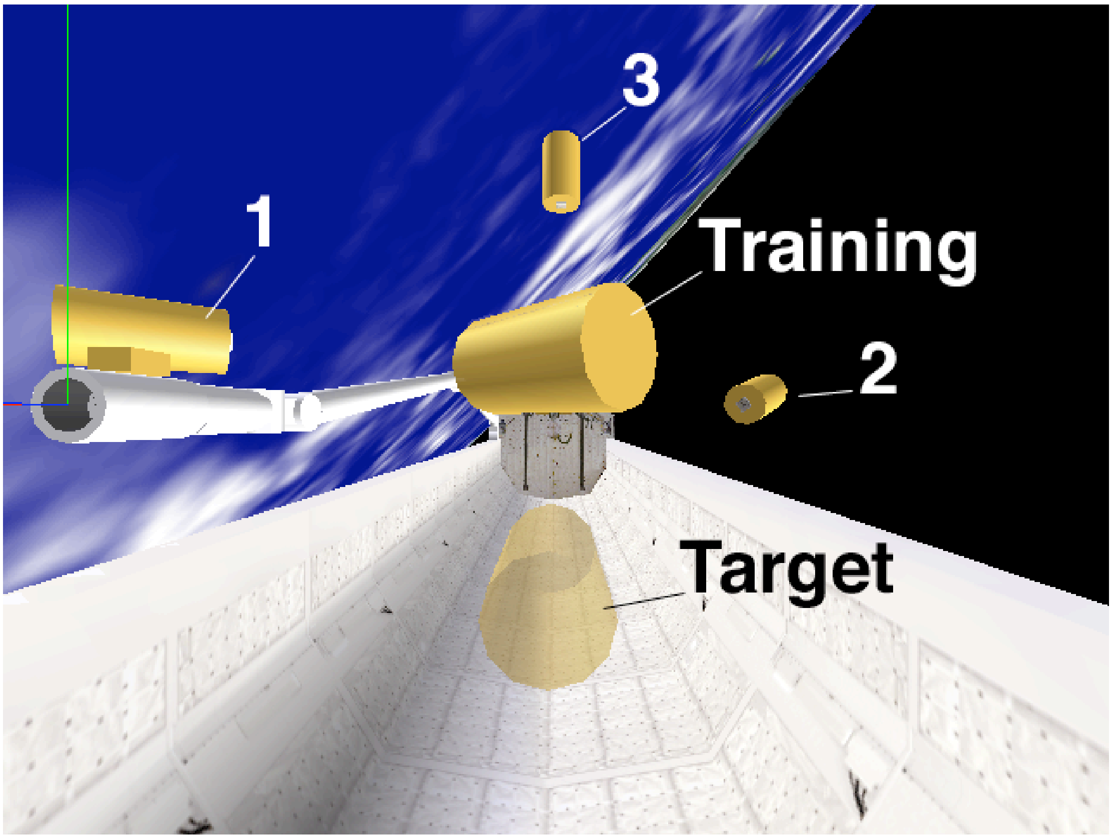


Figure 6. Composite view of the initial arm position, payload locations for training task and test tasks 1-3, and payload target position, viewed from the rear payload bay bulkhead using an artificially wide-angle lens.

2.3 Procedure

2.3.1 Training phase

Each participant read an information sheet giving a brief outline of the experiment's purpose and procedure, filled out a brief questionnaire eliciting some demographic information, completed the pre-experiment Simulator Sickness Questionnaire and signed an informed consent sheet. (See Appendix D for examples of these materials.)

Each participant initially undertook a period in the simulator that served as a familiarisation, training, and initial selection phase. The participant was seated comfortably at the control desk and introduced to the equipment. Operation of the hand controllers and the range of movements that they effect was explained and demonstrated, and the head-mounted display was fitted and adjusted to satisfaction. The participant was then given an automated flyover of the workspace. During the training phase, the participant was free to ask the experimenter questions on the task requirements and the operation of the manipulator.

The participant was trained to use the hand controllers to move the arm to accomplish a simple manipulation Task T, as detailed in § 2.2.3 above. The participant repeated the same training manipulation task under each variation of experimental factors (1) (viewpoint frame of reference) and (2) (control frame of reference) twice, making a total of eight repetitions of the task. In order to pass the initial selection and continue with the second phase of the experiment, the participant was required to take no longer than 3 min to complete each of the last four repetitions. Participants were advised to work as quickly as possible but were not advised of a specific time limit. This was designed to eliminate participants who found the task prohibitively difficult, as well as those with strong susceptibility to simulator sickness. In the experiment, this criterion did not eliminate any participants.

Following the completion of the training phase, participants took a break for 2 to 5 min, during which they could remove the HMD.

2.3.2 Test phase

On beginning the test phase, each participant was instructed that he or she would be given three more increasingly difficult manipulation tasks to be performed, with each task repeated with the four different configurations of displays and controls that he or she had already been exposed to. The participant was advised that there would be a 3-min time limit on each trial and that he or she should work as quickly as possible. The participant was also advised that the experimenter would not answer questions or provide further advice about the task until the completion of the experiment.

The participant repeated each manipulation task under all four variations of the experimental factors: (1) viewpoint frame of reference and (2) control frame of reference, before moving onto the next level of difficulty. Thus, each participant performed a total of 12 trials in the test phase.

At the beginning of each trial, the participant was informed verbally by the experimenter and by an onscreen message for 10 s which variation of factors (1) and (2) they would be operating under for that trial. At successful completion of the task or if the 3-min time limit expired, there was another 10-s pause, meaning a minimum of a 20-s pause before the start of the next trial.

2.4 Performance measures

Participant 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 2. These constitute the primary dependent variables of interest in the experiment.

Table 2. Performance Measures.

Task performance requirement	Task performance measure(s)
Minimise time to complete task.	Total elapsed time from first control action, up to fulfilment of task completion or failure criteria.
Maximise efficiency of path taken during manoeuvre.	Root mean squared (RMS) value of distance between point-of-resolution (POR) on manipulator and target throughout manoeuvre multiplied by duration of manoeuvre.
Minimise 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 such as singularities or at its reach limit.
Minimise control effort.	RMS value of control excursion in all axes throughout manoeuvre multiplied by duration of manoeuvre.

With reference to the table, the RMS value of x multiplied by the duration of measurement is directly equivalent to the time integral of the absolute value of x, which is a scalar measure of *work* done by x. Work is given by the function

$$w = \int_{t_0}^{t_n} |x| \, \mathrm{dt} \quad \text{......} \quad \textbf{(Equation 1)}$$

where $[t_0, t_n]$ is the interval over which measurement occurs. For discrete time systems, the above equation becomes

$$w = \sum_{k=0}^{k=N-1} |x_k| t_d \quad \text{.......... \textbf{(Equation 2)}}$$

where N is the number of samples and t_d is the sampling interval, with $t_d \times N = t_n - t_0$.

In order to produce data for the above performance measures, a number of measures were recorded in real-time:

- Elapsed time (since start of trial).
- Viewpoint position and orientation.
- End-effector position and orientation.
- Payload latch state.
- Control excursion (from centre point).
- Elapsed number of collisions.
- Elapsed number of forbidden arm configurations entered.

From these, any number of secondary measures could be derived. Basic secondary measures derived are presented below and more complex measures are detailed in the results.

The following measures were extracted from data gathered during the unladen phase of each trial:

- Straight-line distance between manipulator end-effector and grapple lug on payload.
- Solid angle between major axis of manipulator end-effector and major axis of grapple lug on payload.

From data collected during the laden phase of each trial, the following measures were derived.:

- Straight-line distance between centroid of payload and centroid of payload target.
- Solid angle between major axis of payload and major axis of payload target.

2.5 Design

The experiment was a factorial design, where combination of factors (1) viewpoint frame of reference and (2) control frame of reference created four distinct experimental conditions, which were repeated in blocks across different levels of factor (3) task. The first two blocks used Task T and constituted the training phase. The last three blocks used Tasks 1, 2 and 3 and constituted the test phase.

Within each block of four trials, there were 24 possible combinations of the ordering of the four conditions. For the initial training task, participants were randomly assigned to a given ordering of conditions, and the orderings were counterbalanced between participants. The within-participant ordering of conditions also changed between tasks. As the total number of combinations required to guarantee complete orthogonality (24^5) was prohibitively high, a systematic ordering was adopted which minimised the number of participants beginning more than one task with the same condition, thus:

Participant number (modulo 24)	1	Order	1,	13,	7,	19,	4
	2		2,	14,	8,	20,	5
	..		..	..	..	..	..
	n		n,	n+12,	n+6,	n+18,	n+3

where a given order number refers to a one of the 24 particular orderings of the four conditions within one task.

3 Results

3.1 Overview of framework used in data analysis

The complexity of the tasks that participants undertook necessitates the establishment of a framework within which results may be described and interpreted.

The experiment was partitioned into two phases, and only data from the latter test phase was considered for in-depth analysis. Although data was recorded from the training phase, during this phase the participant was at various times able to stop and ask questions, or was instructed to try procedures not directly related to the completion of the task, hence the data was not universally suitable for performance comparisons.

The change in performance requirements moving between the three tasks encountered during the test phase was enough to suggest that considering each separately in the analysis would increase the strength of any conclusions drawn from each individual task, at the expense of being able to draw more general conclusions across all three. Hence, the three test tasks are considered separately in most of the analyses below.

Furthermore, each task naturally partitioned into two phases, the first being movement of the arm from its initial resting position and alignment with and latching to the payload, and the second being movement of the arm and connected payload to return the payload to the payload bay and overlay it on top of the payload target. The first phase will be referred to henceforth as the *unladen* phase and the latter the *laden* phase.

3.2 Task completion rate

3.2.1 Motivation for and derivation of measure

The most important raw performance measure was considered to be the time it took participants to complete each trial. In the experimental task, time-to-completion acted as a composite measure of several other performance measures: It incorporated the effects of discrete manipulation errors such as collisions and arm limit conditions, through the 3-s time penalty associated with these errors. It also indirectly incorporated a measure of the control effort required to carry out the manipulation, since time spent erroneously manoeuvring along sub-optimal trajectories, time spent looking about for the correct direction of travel, and time spent backtracking out of areas near the arm limits all consumed control effort, but equally consumed time and hence appeared indirectly in the time-to-completion. Time-to-completion in the experiment thus acted as a composite measure of several competing real-world performance requirements encountered in the work domain of space telerobotic manipulation.

However, raw measures of time-to-completion were of limited use, as many participants found Tasks 2 and 3 difficult and in some cases this difficulty was manifest in the results as trials where the participants failed to complete the manoeuvre within the time limit of 180 s (Figure 7). Thus raw time-to-completion was not a suitable basis for performance comparisons owing to the relatively high number of missing scores. 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 standardised 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.

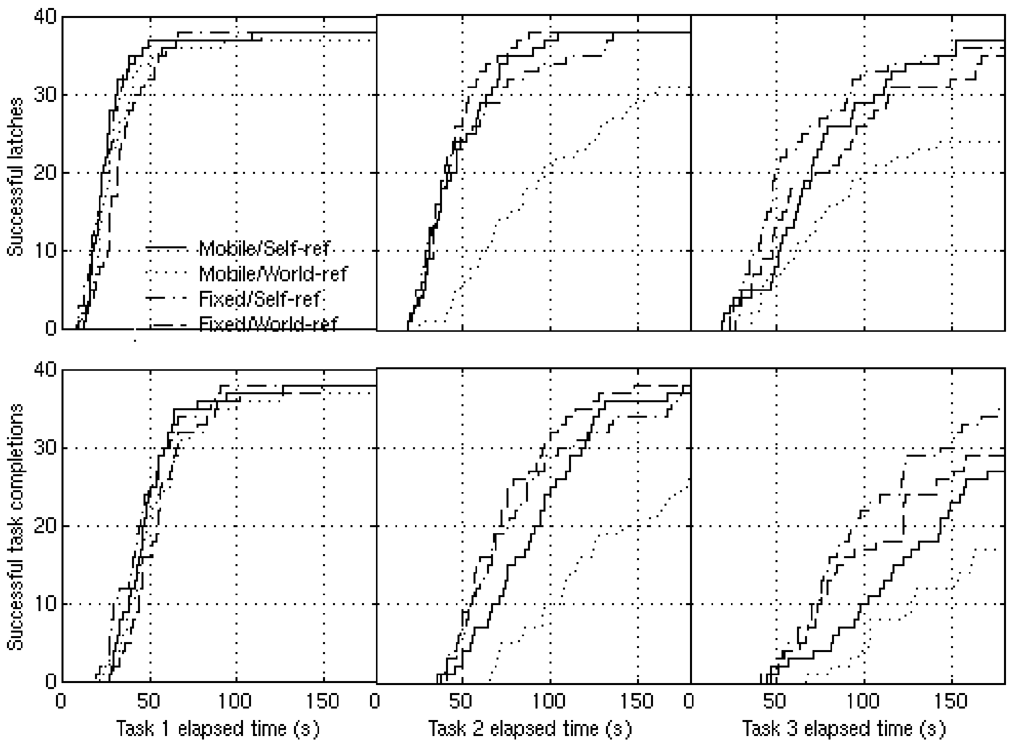


Figure 7. Plot of number of participants (out of 38) who had successfully latched the payload (top row) and completed the task (bottom row) at the elapsed time indicated on the x axis, for Tasks 1, 2 and 3. A greater number of participants breached the 180-s time limit in Tasks 2 and 3, particularly in the mobile/self-referenced condition.

An illustration of the quantities involved in calculation of the progress during a manoeuvre in the unladen phase of a trial in test Task 2 appears in Figure 8. The length of the solid line extending from the initial position of the arm to the latch surface on the payload was standardised at 1.0 for each phase in each task. That is, a complete manoeuvre from the arm's initial position to the payload and back to the target was a progress measure of 2.0, regardless of the task. In Figure 8 the arm progress measure is equal to the length of the arrow labelled "p" divided by the length of the long black axis. The arm progress rate is thus $p / t_{elapsed}$ where $t_{elapsed}$ is the total time taken in the task since the first control action.

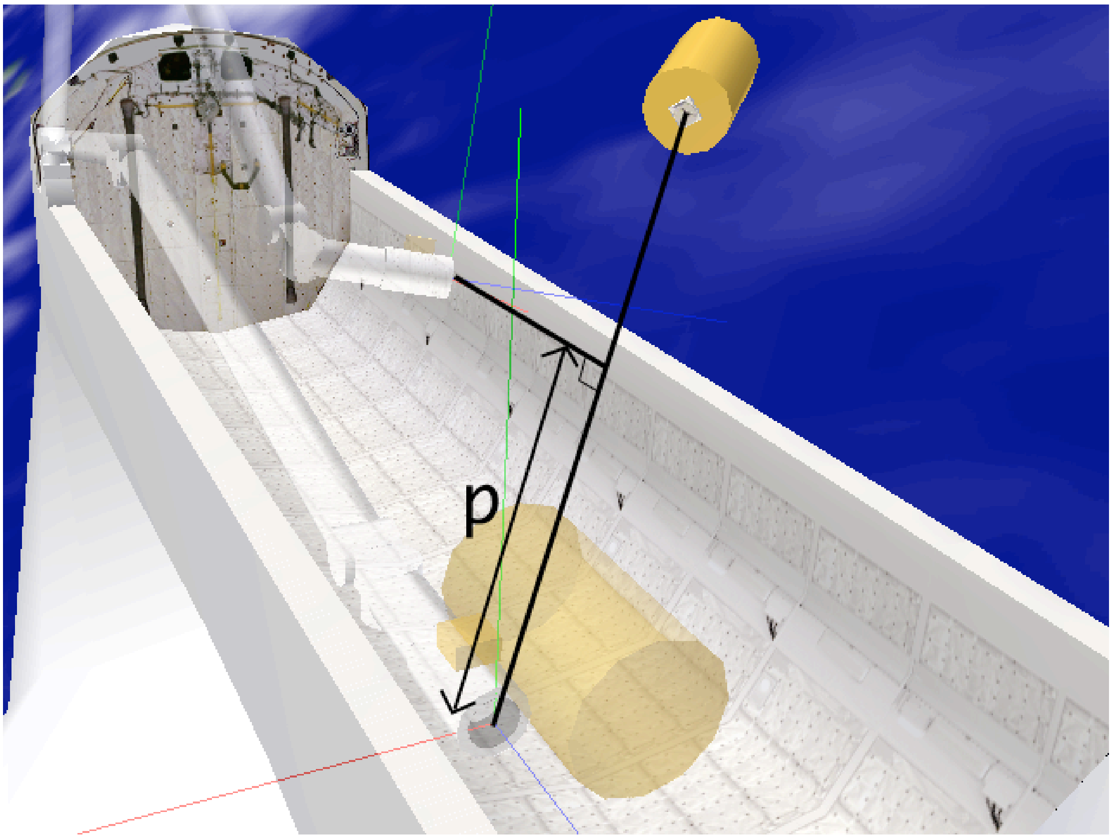


Figure 8. For each task phase, Completion Rate at elapsed time *t* was calculated by determining the projection *p* of the position of the arm at time *t* onto an axis extending between the POR initial and target positions, and dividing by *t*.

The Completion Rate measure as defined above takes into account only the *position* of the POR; progress made by the participant in correctly *orienting* the POR does not contribute to Completion Rate. The reason for this is that an examination of the orientation data suggested that progress made by the participants in orientating the POR varied much less linearly with time elapsed, was far more “bursty” (rapid progress in orientation occurred over much smaller timescales) and was far more prone to indicating reversals away from completion that did not actually affect the time taken to complete the manoeuvre. In short, progress in correctly orienting the payload could be rapidly undone, and reversals in progress could be rapidly corrected. Thus it was felt that the weighting of position versus orientation in a composite completion rate would be somewhat arbitrary and would thus have reduced the meaningfulness of the Completion Rate measure.

3.2.2 Score statistics

The distributions of participants' completion rate scores for the three test tasks appear in Figure 9. Each histogram represents the scores of 38 participants divided into 10 groups. The distributions were approximately normal and of homogenous variance, thus allowing the application of common inferential statistical procedures based on these assumptions.

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 separate test tasks, and are presented in Table 4 in Appendix E.

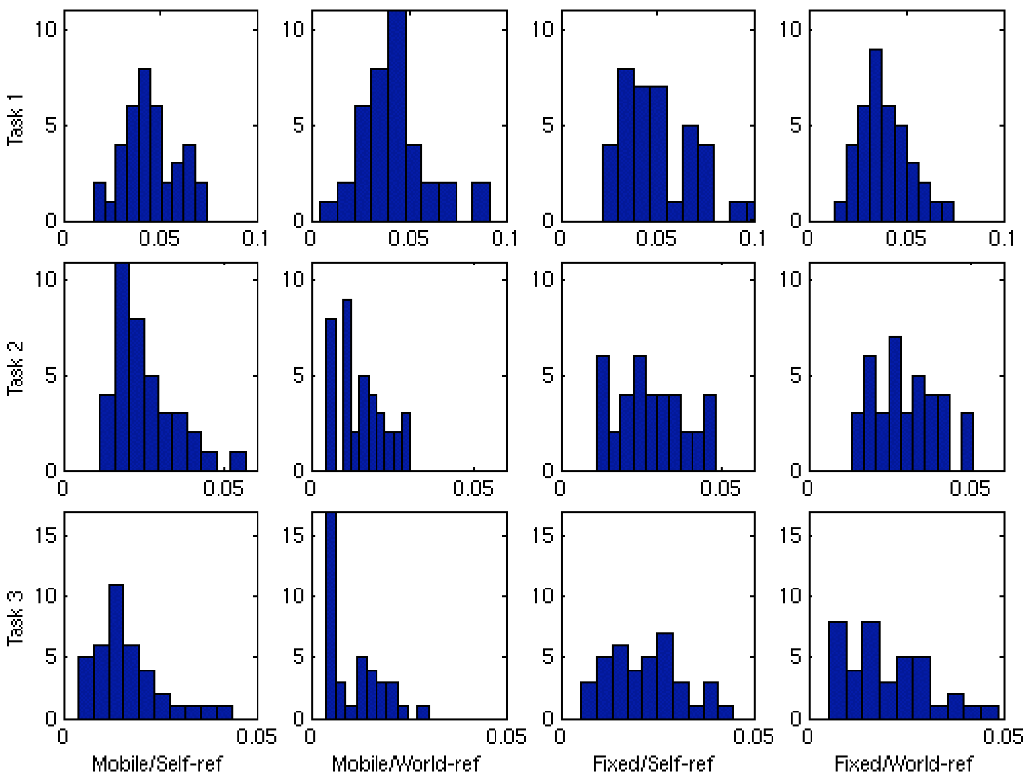


Figure 9. Distributions of participants' task Completion Rate scores. Rows are ordered by test task, columns by experimental condition. (NB: Scale varies between rows.)

3.2.3 Summary of results

The mean Completion Rates for the three tests are displayed in Figure 10 as a function of experimental condition. Within each panel, the four conditions are further grouped by the viewpoint factor and the control frame of reference factor.

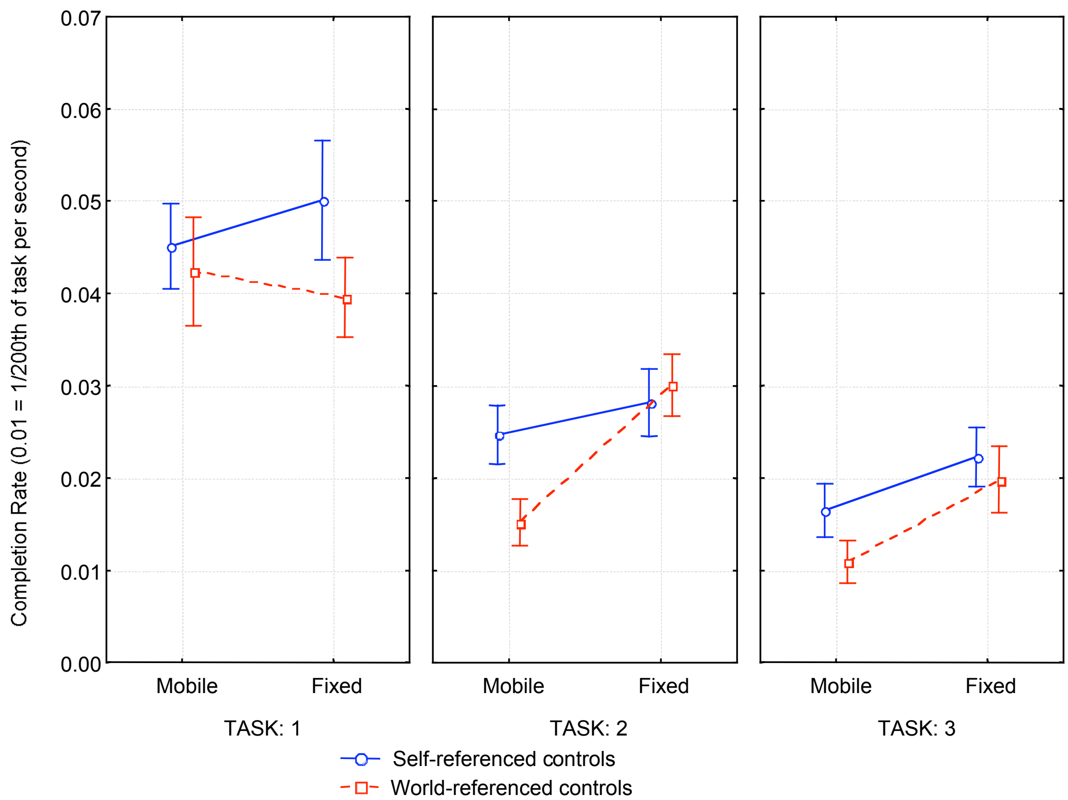


Figure 10. The marginally significant, highly significant and non-significant interaction effects of experimental condition upon mean Completion Rates for test Tasks 1, 2 and 3 respectively. Vertical bars indicate 95% confidence intervals.

In Task 1, participant performance was better when using the self-referenced control frame rather than the world-referenced control frame, a finding supported by the significant main effect for control frame of reference (Figure 11). However, as can be seen from the left-hand panel of Figure 10, there was also a marginally significant interaction between the viewpoint and control frame of reference for Task 1 [$F(1,37) = 3.641$, $p < 0.064$]. The interaction indicates that for Task 1, performance in the mobile viewpoint was little affected by the choice of control frame of reference, whereas in the fixed viewpoint, there was a strong performance decrement imposed by the world-referenced control frame. Application of Tukey's Honestly Significant Different (HSD) post-hoc tests provided support, indicating a highly significant difference between the fixed/self-referenced and the fixed/world-referenced conditions and a marginally significant difference between the fixed/self-referenced and mobile/world-referenced conditions. No other differences were significant.

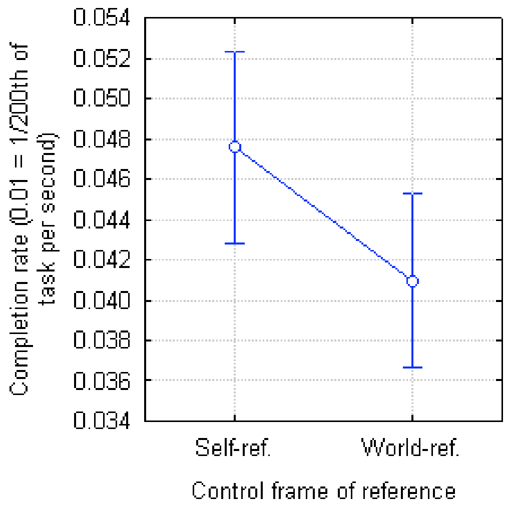


Figure 11. The significant main effect for control frame of reference in Task 1 [$F(1,37) = 9.342$, $p < 0.004$]

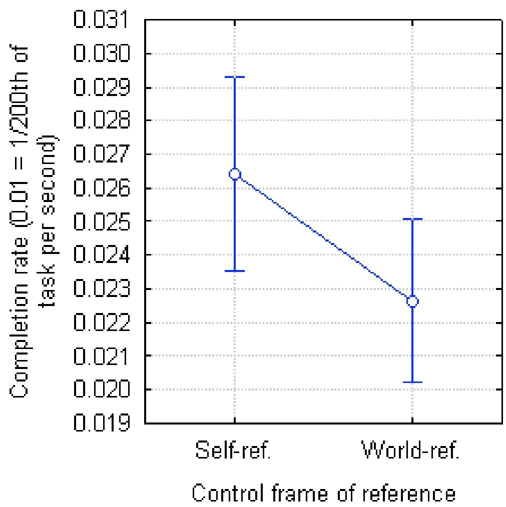


Figure 12. The significant main effect for control frame of reference in Task 2 [$F(1,37) = 12.43$, $p < 0.0011$]

In Task 2, participant performance was again better when using the self-referenced control frame, as indicated by the significant main effect for control frame of reference (Figure

12). Performance was also better from the fixed viewpoint, as can be seen from the main effect illustrated in Figure 13. However, the main effect of viewpoint is again complicated by the interaction of viewpoint and control frame of reference. As can be seen in the centre panel of Figure 10, the interaction indicates that in Task 2, performance from the *fixed* viewpoint was unaffected by the control frame of reference used in performing the manipulation, whereas performance from the mobile viewpoint was strongly affected. A post-hoc application of Tukey's HSD test supported this, indicating highly significant differences between the mobile/world-referenced and the other conditions, and a significant difference between the mobile/self-referenced and fixed/world-referenced conditions, but no other significant differences.

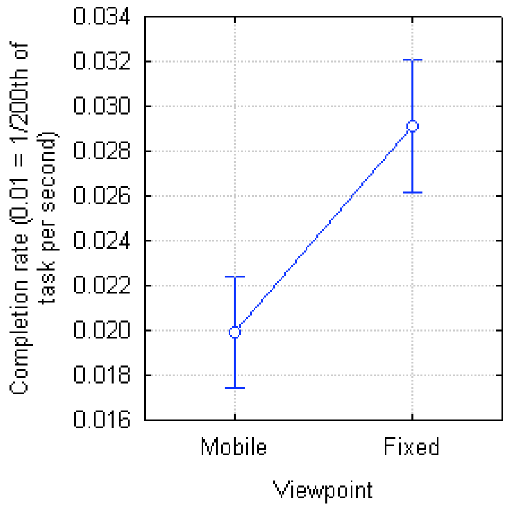


Figure 13. The highly significant main effect for viewpoint in Task 2 [$F(1,37) = 55.71$, $p < 0.000$]

Performance in Task 3 was similar to that in Task 2, proving superior on both the self-referenced control frame and the fixed viewpoint, as indicated in Figure 14 and Figure 15 respectively. The interaction was not significant.

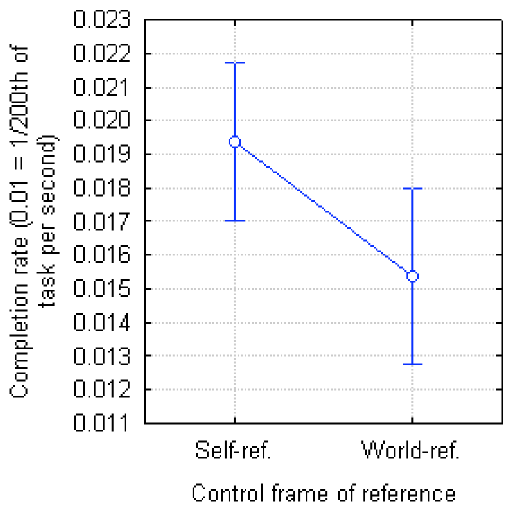


Figure 14. The significant main effect for control frame of reference in Task 3 [$F(1,37) = 10.21$, $p < 0.0029$]

Post-hoc tests indicated caution in making individual comparisons between conditions in Task 3 however. Although the main effect for control frame of reference was significant, Tukey's HSD test for the difference between fixed/self-referenced and fixed/world-referenced was not significant, and neither was the difference between fixed/world-referenced and mobile/self-referenced. In fact, when the Completion-Rate scores were converted into projected time-to-completion scores (by taking the reciprocal and multiplying by 2) it was found that the top three performing conditions were separated by only 32 s (with projected time-to-completion scores of 89 s, 101 s and 121 s) whereas the worst performing condition of mobile/world-referenced was separated from this group by almost twice as much, with a projected time to completion score of 182 s.

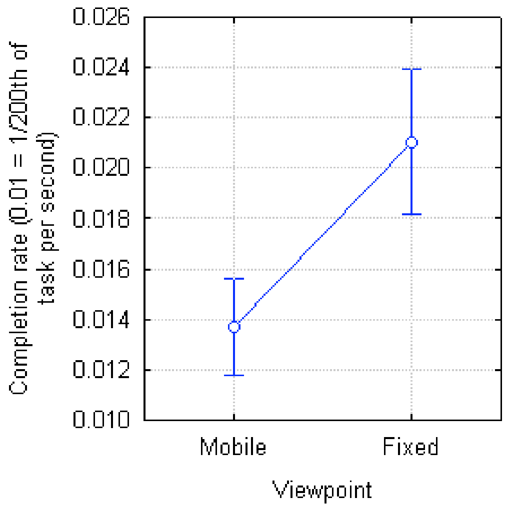


Figure 15. The highly significant main effect for viewpoint in Task 3 [F(1,37) = 36.51, p < 0.0000]

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.

Across all three tasks there was a great deal of variability in Completion Rates between participants. This is evident in the broad spread in the distributions of scores in Figure 9, and is also emphasised by the highly significant F-values for the between-participants intercept terms in the ANOVAs. The standard deviations, expressed as a proportion of the mean, were large, with the average across the four conditions in each of Tasks 1, 2 and 3 equal to 0.37, 0.41 and 0.54 respectively. Further analyses presented below resolve some of this between-participants variability in terms of participants’ styles of control.

3.2.4 Task Completion Rate pre-latch versus post-latch

Exploratory analysis of task Completion Rates over the time course of individual trials for a number of participants indicated that the advantage of certain experimental conditions was felt more at some stages of each trial. The length of time it took participants to manoeuvre the arm from its rest position and latch the payload was generally more than the time it took them to return the latched payload and align it with the target, over all the conditions. However it appeared some conditions favoured post-latch manoeuvres to a greater degree than others.

The ratios of Completion Rate pre-latch to post-latch across Tasks 1, 2 and 3 were derived and were approximately normally distributed. The means of these ratios are plotted in Figure 16 as a function of experimental condition. A higher ratio on a given condition indicates that that condition favoured the post-latch manoeuvre or imposed some handicap upon the pre-latch manoeuvre.

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 separate test tasks, and are presented in Table 5 in Appendix E. In Task 1 there was a marginally significant main effect of viewpoint [$F(1,37) = 4.37$, $p < 0.04$], however post-hoc tests indicated that only the fixed/world-referenced condition was different from the other conditions by a significant margin (Tukey’s HSD, $p < 0.050$). However, the effects of the ratio were far more evident in Task 2. Under the mobile/world-referenced condition, participants generally had considerable difficulty aligning the arm with the latch plate, owing mainly to the fact that during the approach to the payload latch plate the required hand controller actions were in the opposite direction to the onscreen motion they produced. The delays caused by the incorrect control actions made as a result of this display-control incompatibility are evident in the significant main effect for control frame of reference and the highly significant interaction effect. Post-hoc tests indicated that the difference between the fixed viewpoint conditions was not significant, whereas the differences between the pair of fixed viewpoint conditions and each of the individual mobile viewpoint conditions were significant (Tukey's HSD, p < 0.02 for both differences).

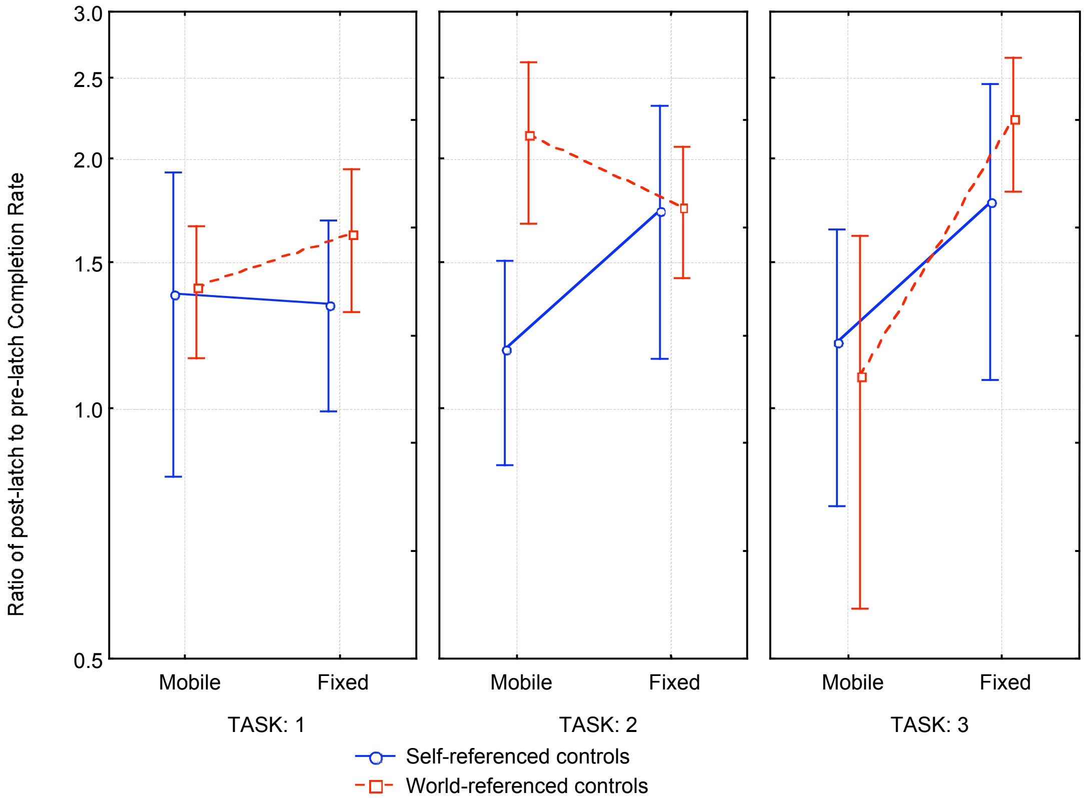


Figure 16. The non-significant, highly significant [F(1,37) = 19.79, p < .000], and non-significant interaction effects of condition upon the ratio of Completion Rate pre-latch to Completion Rate post-latching for Tasks 1, 2 and 3 respectively. The y axis is plotted on a logarithmic scale in order to represent ratios larger than 1.0 on the same scale as a ratios less than 1.0. Vertical bars represent 0.95 confidence intervals.

The effects were different again in Task 3, with the highly significant effect for viewpoint indicating that the fixed viewpoint offered an advantage for the post-latch manoeuvre relative to the pre-latch manoeuvre.

3.3 Manipulation errors: arm limits

3.3.1 Motivation for and derivation of measure

Although commands made through the hand controllers expressed changes in the position and orientation of the point-of-resolution attached to the end of the arm, the motion of this point was bounded by the possible kinematic configurations of the articulated SRMS arm. The bounded kinematics create a *work envelop*e of points that the SRMS may reach and move through. Like other articulated manipulators such as the human arm, the SRMS work envelope is irregular in shape. The extent of the envelope is further restricted under particular orientations of the end-effector, for example facing back towards the shoulder of the arm[1]. At certain points, the SRMS also reaches singularities, where linear motion of the end-effector in a particular direction cannot be maintained because none of the axes of any of the joints has any component acting in the desired direction of travel. [See Nguyen & Hughes (1994) for a more complete discussion of the SRMS singularities.]

Successful manipulation required traversal around the boundaries of the SRMS work envelope and singularities. It is not easy to represent the SRMS work envelope since it is a rather convoluted region in six-dimensional space. Because of this, in the experiment there was no visual aid provided in the virtual environment to represent the SRMS work envelope, and the arm limits and singularities were not directly perceivable. They were indirectly perceivable though, through observing the amount of travel left in each joint. Thus, in order to avoid the arm limits, participants had to either observe the configuration of the arm joints and note when a particular joint was approaching its limit, or else use a trial-and-error strategy. One such trial and error strategy observed being employed by a few participants

[1] This phenomenon also occurs with the human arm, where reach of the tip of the finger is restricted if the hand is required to be held at a particular angle. By way of illustration, try touching the tip of your nose with your little finger while holding your palm facing upwards.

involved the participant identifying areas of difficulty using small-scale exploratory movements and working around these.

Failure to avoid the arm limits not only hindered progression in the task, it also incurred a time and motion penalty in the form of the 3-s backtrack manoeuvre. This particularly affected a small proportion of participants whose control style was typified by rapid poorly-specified exploratory movements of the arm, because the end-effector could travel a considerable distance along an optimal path, only to diverge from optimality at the last instant and strike an arm limit, causing the arm to backtrack over a substantial portion of the path travelled in the seconds prior.

3.3.2 Score statistics

The distributions of participants' *arm reach limit violation count* scores for the three test tasks appear in Figure 17. Each histogram represents the scores of 38 participants divided into 10 groups. The distributions are highly non-normal, enough to prevent the application of common inferential statistical procedures that are based on assumptions of an underlying normal distribution and homogeneity of variance.

In order to assess quantitatively the effect of experimental task and condition on differences in rates of participant arm movement errors, the Friedman ANOVA, a non-parametric equivalent of a one-way ANOVA for repeated measures, was applied to the data. The null hypothesis under test was that the rankings in the scores when grouped by experimental condition were not significantly different from condition to condition, i.e. that the differences in the ranks between conditions were zero.

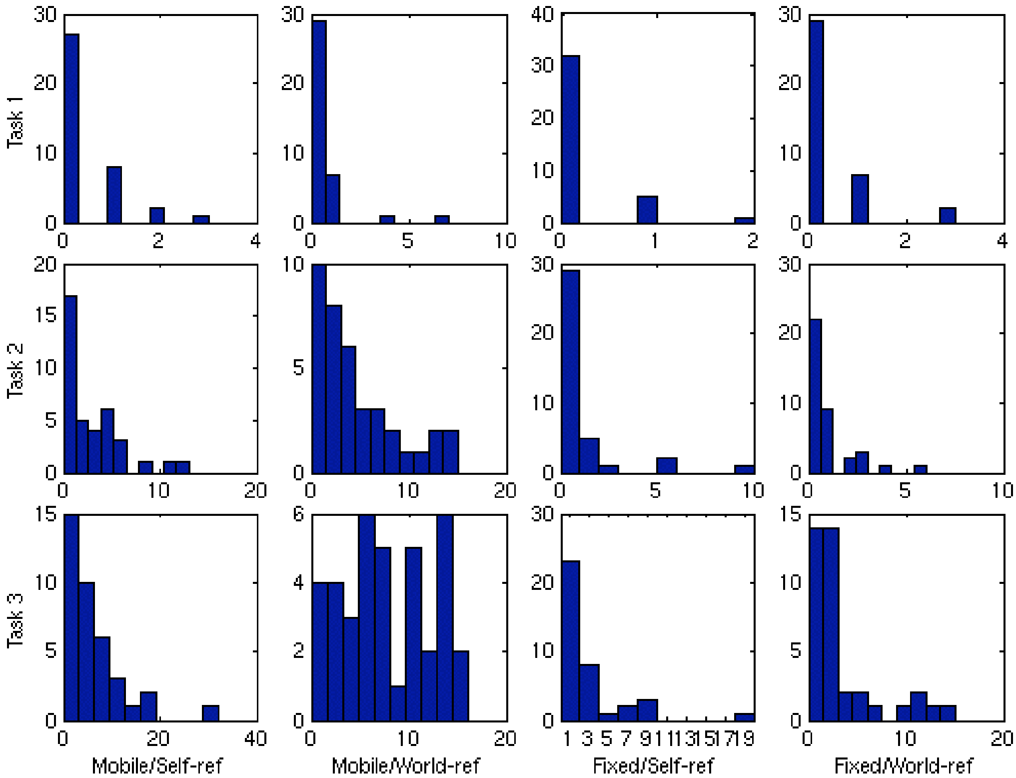


Figure 17. Distributions of participants' *arm reach limit violation count* scores. Rows of graphs are ordered by test task, columns of graphs are ordered by experimental condition. (N.B. Scale varies.)

3.3.3 Summary of results

The distribution of participants' arm limit count scores for the three test Tasks 1 – 3 are displayed in Figure 18, as a function of experimental condition.

The differences in arm limit counts between conditions were not significant for Task 1 [$\chi^2(3) = 2.25$, N = 38, $p < .52$] but were highly significant for both Task 2 and Task 3 [$\chi^2(3) = 48.14$, N = 38, $p < .000$ and $\chi^2(3) = 32.86$, N = 38, $p < .000$ respectively]. Examination of the confidence intervals around the median scores, indicated by the notches in the boxes in Figure 18 indicates that performance in Tasks 2 and 3 was worst under the mobile/world-referenced conditions, followed by the mobile/self-referenced condition, and that the two fixed viewpoint conditions were best, but not significantly different from each other.

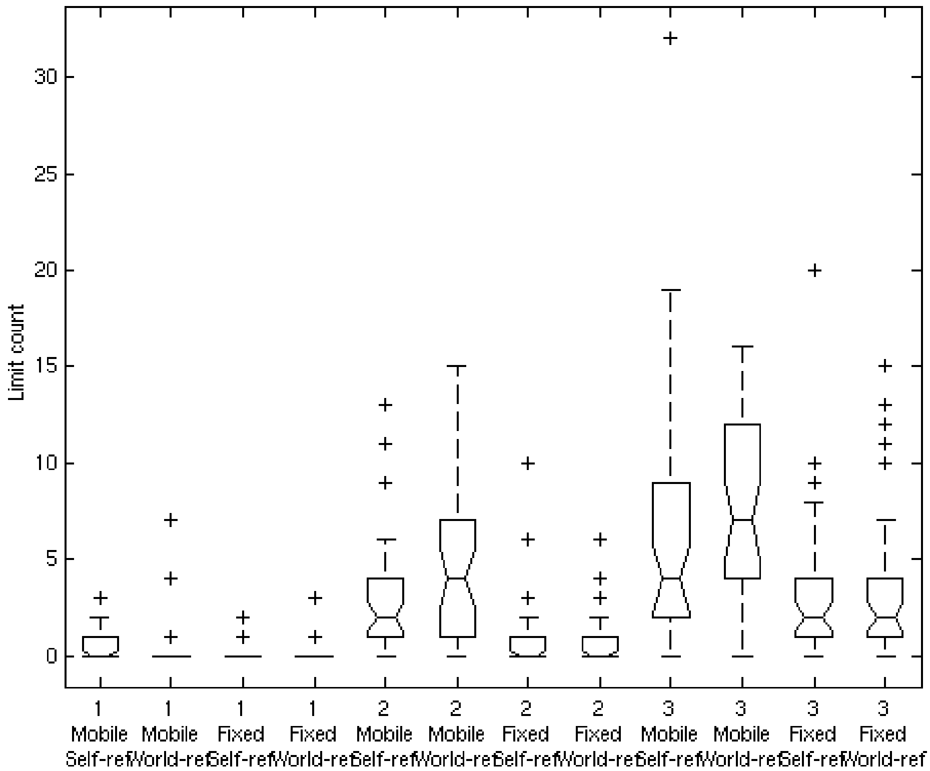


Figure 18. Multiple notched box-plots show distribution of participant *arm reach limit violation count* scores. Each box represents a different combination of task, viewpoint frame of reference and control frame of reference, as indicated by the label beneath. Central line of box is median; upper and lower bounds of box are inter-quartile range (IQR), and whiskers represent spread (excluding outliers). Outliers are defined as values greater than ±1.5 × IQR above or below the box, and are marked by + symbols. The notch in each box represents a .95 confidence interval for the median.

These comparisons of medians effectively amount to multiple planned comparisons, hence should be viewed cautiously with respect to their robustness to Type I errors.

3.3.4 Arm limit violation correlation with time-to-completion

There was a moderate degree of correlation between the number of arm reach limit violations made by participants in each task and performance as measured by projected time to completion. *Projected time to completion* was obtained by taking the reciprocal of Completion Rate and multiplying by 2. The measures were moderately positively correlated, with the values of Pearson's *r* for the correlations equal to 0.66, 0.65 and 0.65 for Tasks 1, 2 and 3 respectively. Some degree of linkage between these two factors is quite understandable considering that each arm limit violation was penalised by 3 s and thus lengthened the time to completion by 3 s. It is useful to quantify the degree of linkage however, and $r^2 = 0.42$ of the variance in projected time to completion in each trial was accounted for by arm limit violations, uniform across all three test tasks.

3.4 Collisions

3.4.1 Motivation for and derivation of measure

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, it does not completely account for one of the most critical determinants of participant performance, that of errors. In the experiment, although the two different types of discrete manipulation errors that the participant could make were penalised in similar ways, they have radically different consequences in real manipulation tasks. Whereas arm limit violations merely impede progress of a manoeuvre, collisions can have catastrophic consequences.

A secondary motivation for analysing the number of collisions occasioned in each condition 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.

3.4.2 Score statistics

The distributions of participants' *collision count* scores for the three test tasks appear in Figure 19. Each histogram represents the scores of 38 participants divided into 10 groups. Similarly to the scores for the arm reach limit violation measure, the distributions are highly non-normal. The Friedman ANOVA was again utilised to assess quantitatively the effect of experimental task and condition on differences in rates of participant collisions errors. As was the case for the arm-limit measures, the null hypothesis under test was that the rankings in the scores when grouped by experimental condition were not significantly different from condition to condition, i.e. that the differences in the ranks between conditions were zero.

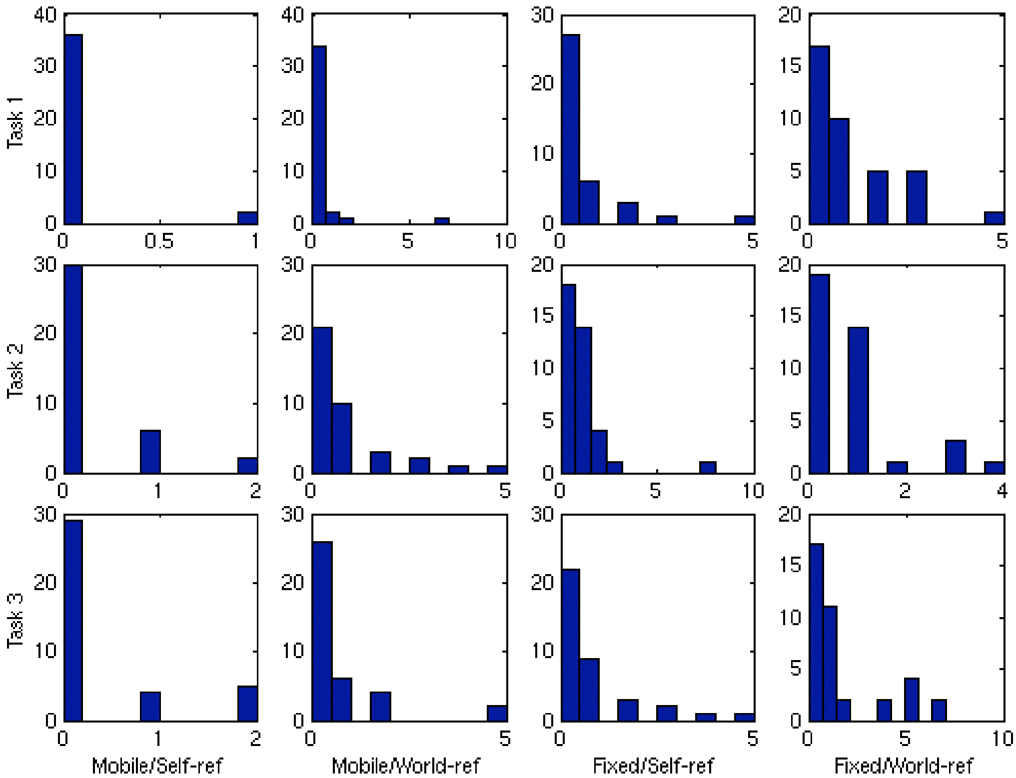


Figure 19. Distributions of participants' *collision count* scores. Rows are ordered by test task, columns are ordered by experimental condition. (N.B. Scale varies.)

3.4.3 Summary of results

The distributions of participants' collision count scores for test Tasks 1 – 3 are displayed in Figure 20, as a function of experimental condition.

The differences in collision counts between conditions were highly significant for Task 1 [$\chi^2(3) = 29.29$, $N = 38$, $p < .000$], marginally significant for Task 2 [$\chi^2(3) = 9.38$, $N = 38$, $p < .024$] and significant for Task 3 [$\chi^2(3) = 12.57$, $N = 38$, $p < .0057$]. Examination of the confidence intervals around the median scores (indicated by the notches in the boxes in Figure 20) revealed a strong first-order effect for viewpoint frame of reference, with the number of collisions under the mobile viewpoint clearly fewer than under the fixed viewpoint in all three tasks.

There was also some degree of second-order interaction between factors in Tasks 1 and 3. In Task 1 the two mobile viewpoint conditions were best for avoiding collisions and not significantly different from each other, whereas the fixed viewpoint condition experienced a higher number of collisions and there was a simple effect of control frame of reference across the two fixed viewpoint conditions. Although there was an increase in collisions in Task 3 under the world-referenced control frame (evident as a rise in the upper quartile and range for both mobile and fixed levels of the viewpoint factor), this increase was potentiated under the fixed viewpoint.

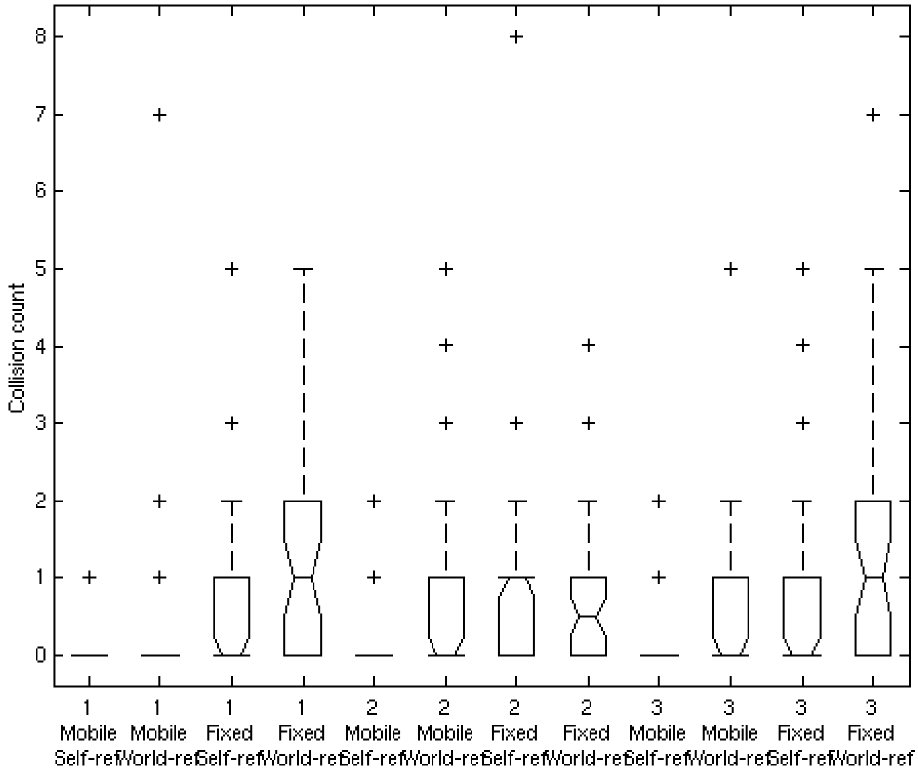


Figure 20. Multiple notched box plots show the distribution of participant *collision count* scores. Each box represents a trial with a different combination of task, viewpoint and control frame of reference, as indicated by the label beneath. Central line of box is median; upper and lower bounds of box are inter-quartile range (IQR), and whiskers represent spread (excluding outliers). Outliers are defined as values greater than ±1.5 IQR above or below the box, and are marked by + symbols. The notch represents a .95 confidence interval for the median.

The prior caution mentioned with respect to visual comparisons of medians effectively amounting to multiple planned comparisons and the resultant increase in familywise Type I error rate also applies equally here.

3.5 Head movements

Although the Completion Rate measures for Tasks 1 – 3 generally indicated a performance advantage for the fixed viewpoint, observations of the participants working in the fixed versus the mobile viewpoint indicated that the performance advantage might have been related to the increased demands upon visual search behaviour necessitated by the mobile viewpoint. An analysis of participant head movement data was conducted to determine the degree to which the amount of head movement made by a participant was differentially influenced by the experimental conditions.

Head movements during each trial were recorded in raw form as a time series of head orientation and position data, and rotational head movement data was derived by calculating the difference in head orientation at each point in the time series. A measure of total rotational work done by the head during each trial was obtained by summing the absolute values of the rotational head movement time series data for that trial. Translational head movement was not considered because translational head movements were primarily a function of the participant's seated posture at the experimental console. Thus they held little relevance to the task requirements and were more likely to be an artefact of natural variability in the head position of a seated participant. Henceforth, references to total head movement will refer to only the rotational component of total head movement work.

The distributions of participant head movement scores for each trial were found to have marked positive skew, and a variance proportional to their mean. A log transform was applied to the data (the natural logarithm, $\log_e$) and this produced distributions with approximately normal shape and uniformity of variance.

A 3 × 2 × 2 (Task × Viewpoint Frame of Reference × Control Frame of Reference) factorial ANOVA with repeated measures on all three factors was conducted, and is presented in Table 6 in Appendix E. Head movements increased with task difficulty (in order of Tasks 1 – 3) and were substantially larger under the mobile viewpoint, as indicated by the highly significant main effects for task and viewpoint frame of reference [$F(2, 74) = 303.1$ $p < .000$, and $F(1,37) = 851.1$, $p < .000$ respectively]. Post-hoc analysis of differences between the means using Tukey's HSD test indicated that all differences were significant between these main effects.

Additionally the first-order interaction of task and viewpoint frame of reference was significant. The interaction is plotted in Figure 21 and appears to indicate a slightly non-uniform difference in head movements between the two viewpoints from Task 2 to Task 3. This difference, although statistically significant is too small to be of any practical significance.

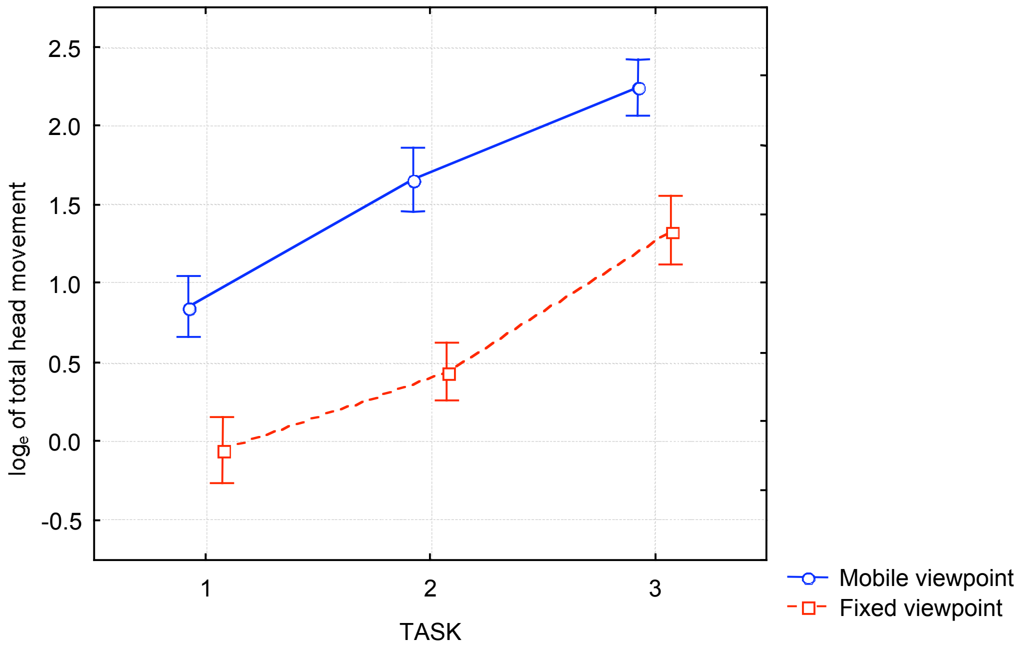


Figure 21. The significant interaction [$F(2,74) = 19.79$, $p < .000$] of task and viewpoint frame of reference on log$_e$ of total head movements per trial. Vertical bars represent 0.95 confidence intervals.

3.6 Hand controller work

A second direct measure of the physical work done by the participant in each trial was that done by the hand controllers. Analysis of hand controller data was performed in order to test the hypothesis that the total work done on the hand controls was a function of the experimental condition.

Hand controller actions were recorded in raw form as a time series representing the excursion of each hand control from its rest point. The hand controllers were both rate controllers, where a constant excursion from the rest position specified a constant rate of change in position or orientation. A discrete-time integration operation (Equation 2) was performed on the hand controller data over the duration of each trial in order to obtain a measure of the total work done by the hand controller during that trial. Raw readings from both hand controllers were standardised so that maximum excursion in one axis was represented by the value 1.0 for that axis. This allowed both position and orientation measures to be summed to produce a composite total bimanual control work measure for each participant in each trial.

A 3 × 2 × 2 (Task × Viewpoint Frame of Reference × Control Frame of Reference) factorial ANOVA with repeated measures on all three factors was conducted, and is presented in Table 7 in Appendix E. There were significant main effects for task and viewpoint frame of reference, and a marginally significant main effect of control frame of reference [$F(2,74) = 152.3$, $p < .000$; $F(1,37) = 20.76$, $p < .000$; and $F(1,37) = 5.70$, $p < .022$ respectively.] There were also significant first-order interaction effects of task and viewpoint frame of reference and a significant three-way interaction between task, viewpoint frame of reference and control frame of reference [$F(2,74) = 7.34$, $p < .0012$; and $F(2,74) = 5.18$, $p < .0078$ respectively]. A plot of the three-way interaction appears in Figure 22.

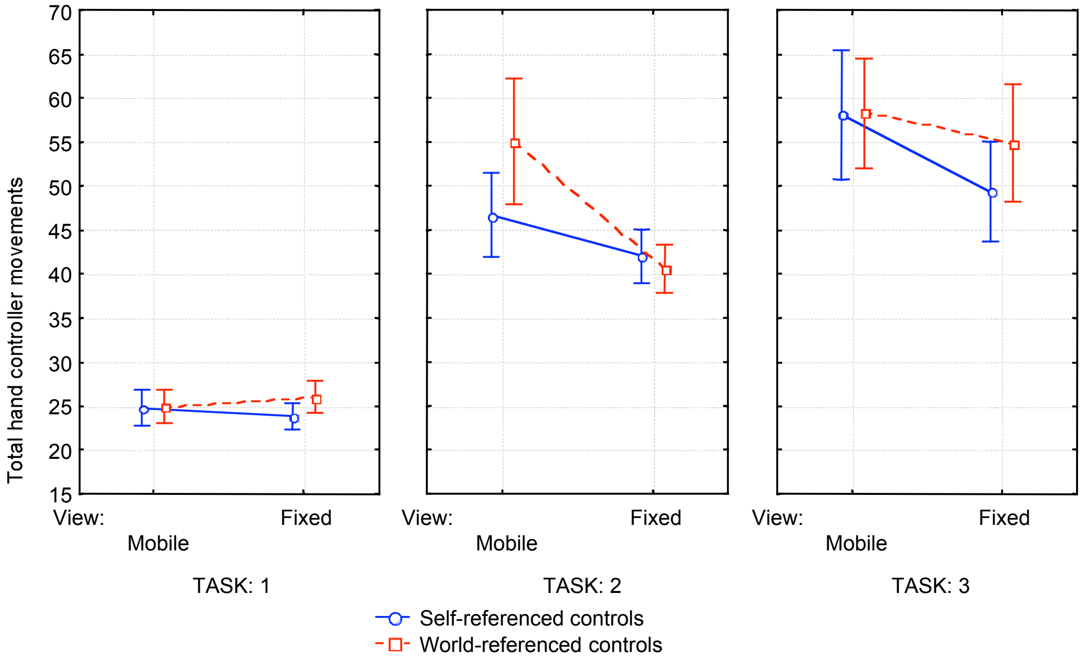


Figure 22. The significant three-way interaction effect of task, viewpoint frame of reference and control frame of reference on total hand control work. [F(2, 74) = 5.18, p < .0078]. Vertical bars represent 0.95 confidence intervals.

Post-hoc individual comparisons were made using Tukey's HSD test in order to identify the significant differences between conditions within each task. None of the comparisons between conditions in Task 1 were significant, indicating that participants did not expend more control effort manoeuvring the payload in any one condition in Task 1.

The results for Tasks 2 and 3 appear to be the mirror image of the results found in Tasks 2 and 3 on the Completion Rate measure (see Figure 10, p36) and this reciprocal relationship is supported by the fact that in Tasks 2 and 3, the set of significant differences between conditions that emerged matched pair-for-pair those observed in post-hoc comparisons of the Completion Rate results. This reciprocal relationship indicates that those conditions that were associated with slower rates of completion were also associated with increased total hand control work.

To further characterise this negative linkage between Completion Rate and total hand control work, Pearson's r measure of correlation was calculated across all participants and all trials for Tasks 1 – 3 and a moderate negative correlation was found, $r = –0.67$, $r^2 = 0.45$.

3.7 Simulator sickness effects

3.7.1 Simulator sickness statistics

Intolerable simulator sickness effects were felt by 6 of the 45 participants in the sample. These participants withdrew from the experiment prior to completing the test phase. No participants withdrew prior to the commencement of the test phase.

Subjective simulator sickness effects were evaluated using a slightly modified version of the Simulator Sickness Questionnaire (Robert S. Kennedy, Lane, Berbaum, & Lilienthal, 1993). The change in SSQ scores from pre-experiment to post-experiment measured over all 45 participants was found to be an increase with a mean of 142.7 points on the SSQ scale and a standard deviation of 242.8. This includes eight participants who experienced a *decline* in SSQ-related symptoms over the duration of the experiment. These participants verbally reported a high degree of engagement with the simulation.

3.7.2 SSQ correlates

Over all 45 participants there were no significant correlations between change in SSQ from pre-experiment to post-experiment and either reported level of prior simulator experience (r = –0.1), or gender (r = 0.24).

For the 38 participants who completed the experiment, there were low positive correlations between change in SSQ and total rotational head movements made by the participant (r = 0.45, $r^2 = 0.20$), and total control work made by the participant (r = 0.38, $r^2 = 0.14$). There was no correlation between change in SSQ and overall participant performance as measured by mean Task Completion Rate over the 12 test trials (r = –0.1) and a low positive correlation with participant performance as measured by total number of arm limit errors and collisions (r = 0.39).

3.7.3 Verification of SSQ efficacy against objective measures

Although the SSQ has proved efficacious in its use elsewhere (Robert S. Kennedy et al., 1993), it remains a self-report measure, and thus potentially open to subjectivity and misreport. It has been noted that it has shortcomings in accounting for some motion sickness effects (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001). In one strong example where the SSQ failed to account for a participant's simulator sickness symptoms in this experiment, a participant who withdrew because of intense discomfort did not rate any of the SSQ symptoms higher than *slight* on the post-experiment SSQ. Yet this participant withdrew earlier than anyone else and also experienced the longest duration after-effects, reporting verbally to the experimenter that he had felt sustained dizziness and disorientation for 14 hours after the experiment.

Although no direct objective measurements of simulator sickness-related factors were made in this experiment, one objective measure was available in the form of a categorical division of participants into those who withdrew part way through and those who completed the experiment. The correlation between changes in SSQ scores from pre-experiment to post-experiment and early withdrawal from the experiment was calculated in terms of Pearson's point-biserial coefficient, and change in SSQ scores was found to account for only 16% of the variance in early withdrawal, $r_{pb} = 0.396$, N = 45. The correlation is indicated graphically in Figure 23.

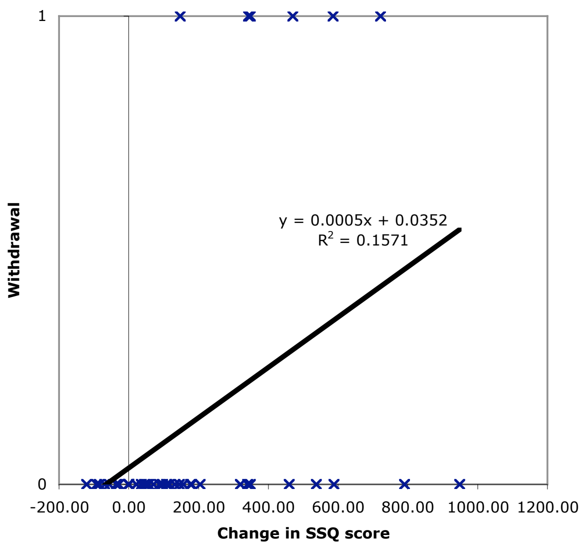


Figure 23. Graphical determination of point-biserial correlation between change in SSQ scores and early withdrawal due to simulator sickness. Early withdrawl is scored as 1.0 on the y axis, completion without withdrawal as 0.0. The slope of the regression line is equal to Pearson's point-biserial measure.

Based on this analysis, the utility of using change in SSQ scores as a measure to identify participants experiencing intolerable simulator sickness effects is questionable.

3.7.4 Gender effects

Gender differences in susceptibility to simulator sickness have been reported in the literature (Robert S Kennedy, Lanham, Massey, & Drexler, 1995). In this experiment, although females accounted for 10 of the 45 participants tested, they accounted for 3 of the 6 participants who *withdrew* from the experiment due to the intensity of simulator sickness effects they were experiencing. However, the one-tailed χ^2-Test of Homogeneity of the hypothesis that females were more likely to *withdraw* due to simulator sickness than males was not significant at the 5% level ($\chi^2(1) = 3.091$, $p < .079$), indicating that random sampling variation cannot be ruled out as the source of the higher proportion.

3.8 Demographics

3.8.1 Prior simulation experience

Distribution of participants prior experience with 3D computer generated environments was assessed via self-reported number of hours, and was categorised into five broad categories each varying by an order of magnitude. The distribution of the 38 scores for those participants who completed the experiment is depicted in Figure 24. As can be seen, there was a broad spread of experience levels, and the experience levels were reasonably well distributed amongst the categories, with the exception of the 50 – 500 hours category. The relatively high number of participants in the upper categories owed perhaps to the relatively high proportion of participants who were engineering students.

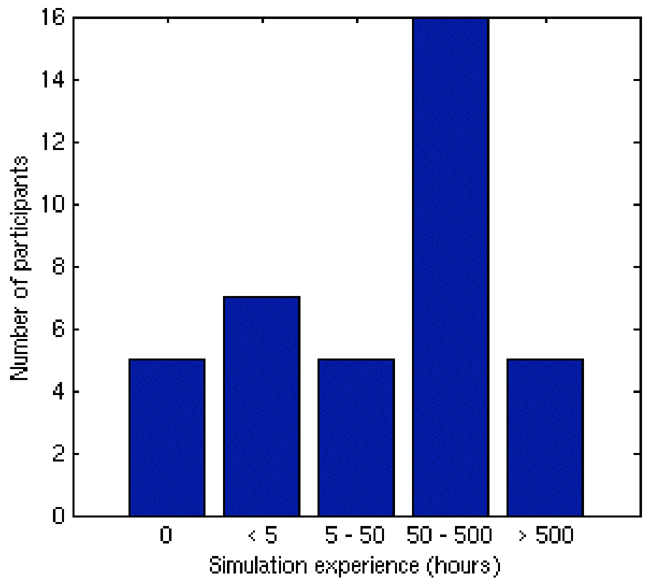


Figure 24. Distribution of participants' reported prior simulation experience.

Participants' reported level of simulation experience was compared against three different measures. Performance on task Completion Rate, averaged for each participant over all trials in Tasks 1, 2, and 3, was not correlated, $r = 0.23$. Performance as measured by total number of arm limit errors and collisions for each participant was moderately negatively correlated, ($r = -0.51$, $r^2 = 0.26$) indicating that to a small degree participants who were more experienced made fewer manipulation errors. Lastly, in order to determine whether more experienced participants were more efficient in respect of expending less control effort to complete the task, a measure of *control intensity* was formed for each participant by summing the total hand controller movements over all trials in Tasks 1, 2 and 3 and dividing by the reciprocal of the averaged Completion Rate over the same trials. This measure showed no correlation with simulator experience, $r = -0.20$.

3.8.2 Gender effects

Comparisons were made between males and females to test for significant performance differences on the basis of gender. Two measures that appear above were reused: average task Completion Rate for each participant over all trials in Tests 1, 2 and 3, and total number of manipulation errors over the same trials. The distributions by gender of participant scores on these measures are illustrated using notched box plots in Figure 25 and Figure 26.

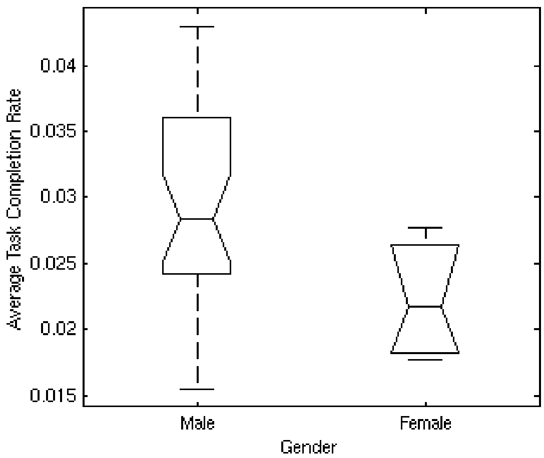


Figure 25. Notched box plot indicating distribution of participants' performance scores on average Completion Rate. Higher y values indicate better performance.

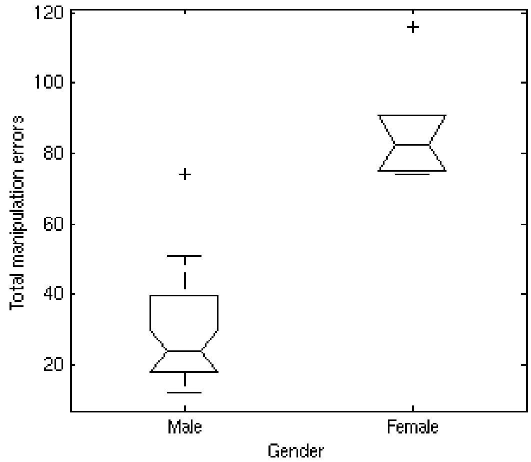


Figure 26. Notched box plot indicating distribution of participants' performance scores on total number of manipulation errors. Lower y values indicate better performance.

Male performance was found to be significantly higher than female performance on both measures. One-tailed t tests for two independent samples were applied to the performance measures to test the directional hypothesis that male performance was better than female performance and were significant on both measures, $t(36) = 2.48$, $p < .009$ for average Completion Rate, and highly significant, $t(36) = -8.57$, $p < .000$, for total number of manipulation errors.

4 Discussion

4.1 Comparison of ego- and exocentric virtual environments

This study evaluated whether space-based manipulation tasks performed telerobotically showed 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. Each of the two frames of reference was factored across two dimensions, viewpoint location relative to the end of the arm and control frame of reference relative to the end of the arm.

On the performance measure of task completion rate, there was a trend across all three tasks towards better performance with the combination of fixed viewpoint and the self-referenced controls. The fixed/self-referenced condition is a cross between the viewpoint typically found in a purely exocentric interface and the control frame of reference typically found in a purely egocentric interface.

On the performance measure of manipulation accuracy as indexed by collision count there was a strong effect across all tasks in favour of the mobile viewpoint. However the mobile viewpoint was associated with a substantially higher number of arm reach limit violations in Tasks 2 and 3, as well as higher total head movements.

Total head movement also increased with the task difficulty as measured by task completion rate, suggesting it was a contributor to task difficulty. Lower completion rates were also associated with increased control effort.

There were no significant correlations between change in simulator sickness as measured by the SSQ, and performance, gender or prior simulator experience. The SSQ measures failed to account for the symptoms of the 5 participants who withdrew from the experiment because of simulator sickness. Prior simulator experience was weakly associated with fewer manipulation errors. There were significant effects of gender on performance as measured by average task completion rate and total number of manipulation errors.

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 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.

4.2 Viewpoint performance issues

The mobile viewpoint conditions offered clear performance advantages over the fixed viewpoints in terms of reduction in number of collisions. However, the mobile viewpoint conditions were inferior in their support for perception of the arm work envelope and avoidance of arm reach limit conditions.

There are a number of reasons why the mobile viewpoint did not show better performance than the fixed viewpoint. Firstly, although it increased the support for avoiding collision, it reduced the support for perceiving the edge of the arm's reach envelope and therefore avoiding arm reach limit conditions. Secondly, in Tasks 2 and 3 where there were higher degrees of misalignment between the payload and the payload target, the fixed viewpoint allowed the comparison of the relative positions of the payload and target with fewer head movements than the mobile viewpoint. Thirdly, the combination of the mobile viewpoint and world-referenced control frame suffered particularly from the deleterious effects of increasing misalignment between control action and observed effect. Further explanations and possible origins of these results are presented below along with discussion of ways in which the performance disadvantages of the mobile viewpoint might be alleviated in order to better support performance during the transport phases of the manipulation tasks.

4.2.1 Arm reach limit violations

Considering the significant effect of viewpoint on arm reach limit violations, there were substantial and obvious differences in the utility of the two different viewpoints, fixed and mobile, for the activity of observing the arm configuration. From the fixed viewpoint, it was generally possible to keep both the arm and the payload in sight. However from the mobile viewpoint, keeping both the arm and payload in sight typically involved considerable head movement by the participant; in one direction to observe the payload, downwards to observe the wrist joints (above which the mobile viewpoint floated) and in a different direction to observe the shoulder and elbow joints. It was observed that participants found these head movements difficult and, in some cases, reported them to be disorientating as well.

The moderate proportion of variance in projected times-to-completion accounted for by arm limit violations indicates that participant performance as measured by completion rate was dependent on the participant's ability to avoid arm limit violations.

The different tasks themselves also imposed quite diverse constraints on the arm movements and thus each task required a different approach to planning the manoeuvre. These differing constraints arose by virtue of the fact that the differing payload positions between tasks lay in a different part of the arm's work envelope. The arm itself is kinematically complex, and its work envelope is a highly irregular six-dimensional space.

The irregular shape of the SRMS's work envelope was a significant confounding factor in application of a mobile viewpoint to the SRMS control interface. The deleterious effect of the mobile viewpoint on performance as measured by arm reach limit violations in Tasks 2 and 3 suggests that in manipulation tasks which required manoeuvring near the edge of the arm work envelope, such as Tasks 2 and 3, the mobile viewpoint restricted the participants' ability to perceive and avoid arm reach limit and singularity conditions.

In general, those participants who performed well appeared to follow strategies that involved avoiding the edges of the arm's work envelope. Although the only explicit information provided about the arm's work envelope was the warning tone and backtracking that occurred when the arm reached the boundary, it was possible to observe the arm's joints and see that for a particular arm position, some control actions were more likely than others to move particular joints to the end of their range. At the same time, participants knew (and some commented) that they were working under a time limit and thus could not afford to spend too much time scrutinising the arm joints before each control action.

A number of strategies have been considered in the computer graphics literature to address the problem of displaying volume boundaries in three-dimensional space (Kaufman, 1991). Some of these display the boundary as a parametric coloured membrane in 3D space, others use volume rendering techniques such as applying a fog effect that increases in opacity as proximity to the boundary decreases. The SRMS workspace however is six-dimensional, and even slight rotations of the tool can drastically change its structure and layout. One strategy with potential is to represent proximity to the boundary surface by means of force feedback upon the manipulator controls. This approach has been successfully applied in the domain of analytical chemistry (Brooks, Ouh-Young, Batter, & Kilpatrick, 1990) and holds potential for telemanipulation interfaces such as that of the SRMS.

4.2.2 Mobile viewpoint and increased head movements

The mobile viewpoint conditions were associated with significantly higher total head movements than the fixed viewpoint conditions. This result originated from both an increased requirement for visual scanning behaviour to acquire views of the target, and increased visual scanning to gauge joint positions in cases when the arm reach limit was violated.

Increased demands on head movement in the mobile viewpoint conditions were particularly evident in the first attempt at each task from the mobile viewpoint. Participants were observed making much faster and greater head movements to acquire their first sight of the free-flying payload from the mobile viewpoint than to gain first sight of the payload from the fixed viewpoint.

This was perhaps an unfortunate consequence of the selection of the initial arm position in the experiment's design. Although the initial arm end-effector position was the same between conditions, and therefore the task requirements of the manipulation were the same across viewpoint conditions, the particular choice for the initial arm position (i.e. the rest position alongside the payload bay) failed to control the participants' *initial* viewpoint across viewpoint conditions. With the arm in its rest position, the initial viewpoint location for the mobile viewpoint conditions was near the rear of the payload bay whereas in the fixed viewpoint conditions it was at the front of the payload bay. Thus quite a considerable distance separated the initial viewpoint locations. Controlling this variable in follow-up experiments is desirable and could be easily achieved by selecting the initial arm position such that the mobile and fixed viewpoints are coincident at the initiation of each trial.

4.2.3 The mobile / world referenced condition

Considering performance in the mobile viewpoint, the difference in performance between the mobile/self-referenced condition and the mobile/world-referenced condition varied approximately in proportion to the degree of misalignment between the control axes and the viewed effects of control actions. In Task 1 there was 45° difference between the control axes and their viewed effects, and the performance difference between the two mobile viewpoint conditions was not significant. In Task 2, this misalignment was approximately 135°, and the performance difference between the two mobile viewpoint conditions equated to 50 s extra to complete the task under the world-referenced control mode. In Task 3 the misalignment was 90°, which equated to completion of the task taking an extra 62 s.

4.3 Collisions and speed-accuracy tradeoffs

Each task offered a diverse set of constraints on successful task performance, and reflecting this, participants adopted a variety of different strategies in their performance. Some chose cautious strategies, making small test control actions prior to large-scale actions, and backing carefully out of areas of difficulty. Others were less cautious and even reckless, frequently making large control actions and often repeatedly getting into areas of difficulty, in a kind of noisy-search strategy.

Typically, explanations of causative mechanisms of speed-accuracy tradeoffs are expressed in terms of Fitts' Law-type explanations (Fitts, 1954); (MacKenzie, 1992), such as controller servo gain versus momentum. It is more difficult in the manipulation task in this experiment than in other types, such as two-dimensional pick-and-place tasks, to explain the origins of the trade-off in terms of a straight Fitts' Law account. There are broad differences between the fixed and the mobile viewpoints in their support for control of accurate fine movement when the manipulator is close to the payload. One intrinsic difference between the viewpoints is the distance from the viewpoint to the point-of-resolution under control. The intention in this experiment was the study of a work environment with a spatial layout as analogous as possible to the real SRMS workspace, and therefore no attempt was made to control for this factor, just as no attempt was made to control for the ability of the participant to see both the payload and the arm joints, a factor which affected the ability of the participant to avoid arm limit conditions. Thus, the overall speed-accuracy tradeoffs may owe more to interactions between the viewpoint and competing task performance constraints than to lower-level explanations in terms of Fitts' Law.

The two phases of each trial also posed differing constraints, some of them independent of the task condition the trial was being performed under, others dependent to varying degrees. The constraints on consequences of overshoot constitute one such difference. In the unladen phase, overshooting the desired target (the latch plate) with the end-effector typically resulted in a collision between the arm and the payload. In contrast, in the laden phase, small to moderate overshoot of the payload target position caused no collision. In fact, the smallest clearance while manoeuvring the payload into the target position was 0.88 m to the floor of the payload bay, a much greater clearance than that available when attempting to align the end-effector with the payload grapple fixture.

4.4 Body-referenced frames in the space environment

Results from previous studies 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 (Bennett, Mucignat, Waterman, & Castiello, 1994; Soechting, Tong, & Flanders, 1996). 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, and the mobile viewpoint, which offered better conditions for perceiving and controlling alignment between the end-effector and payload was superior, as evidenced by a reduced number of collisions between payload and end-effector.

4.5 Visual alignment effects

Results from Tasks 2 and 3 in favour of the fixed viewpoint 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 the 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.

4.6 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 results, drawn primarily from studies of frames of reference in navigation tasks (McCormick et al., 1998; Olmos, Wickens, & Chudy, 2000; Wickens, 1999).

There are a number of crucial differences between these studies and the situation studied in this experiment, however. The most important difference relates to the constraints on the possible configurations between the item being controlled and the environment in which it acts. In the study by Olmos, Wickens and Chudy, 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. Thus in hindsight, greater experimental control and possibly an alleviation of some of the disadvantages of the mobile viewpoint could have been achieved by adopting a more general definition of viewpoint frame of reference.

Although fixing the position of the world-referenced viewpoint may be entirely appropriate for a navigation task, keeping the viewpoint fixed in position is not an essential dimension of an exocentric viewpoint frame of reference. Viewpoint frame of reference is more strongly influenced by whether the relative *orientations* of the viewpoint and object under control are linked, rather than whether their *positions* are linked or not. The viewpoint could thus be *mobile* and yet still be aligned to an exocentric frame of reference.

In light of this clarification, selecting a more general set of constraints on the differences between the two viewpoint frames of reference might alleviate some of the uncontrolled differences in the information available via the two viewpoints. Specifically, it would be possible to control for a major confounding factor in the experiment, that of the distance between the viewpoint and the end of the arm. The exocentric viewpoint would remain at a fixed orientation to the base of the robot arm but would move so as to maintain a set distance from the mobile end-effector. Conversely, the egocentric viewpoint would remain at a fixed orientation relative to the end-effector, but would also move so as to maintain a set distance from the mobile end-effector.

4.7 Gender effects

Comparison of performance between males and females indicated significant differences on the basis of gender. There exists a literature indicating that gender differences are to be expected in mixed-spatial tasks (e.g. Nordvik & Amponsah, 1998; Stumpf & Eliot, 1995). Typically, men have been found to perform better than women in tasks requiring mental rotation of three-dimensional objects and relative spatial judgements in three dimensions. The manipulation tasks in this experiment had high demands on spatial perception/action coordination, and thus the observed performance differences between genders support the previous findings. A note of caution about the robustness of this result does need to be sounded however since there was a large disparity in the numbers of participants in each of the two groups, with only 6 females. Hence, although the performance differences were large in magnitude and statistically significant, the addition of only a few more well-performing female participants had the potential to nullify this result.

4.8 Application of findings

The applicability of the findings of this experiment is not limited to zero-gravity space environments. The distinguishing features of the zero-gravity space-based environment are essentially the properties of an environment freed from the effects of a constant unidirectional acceleration and the reference plane that such a unidirectional acceleration naturally creates. However, diminishing or removal of the effects of our most dominant unidirectional acceleration, the gravity of Earth, is not limited only to space outside Earth's orbit. There are many Earth-based domains where Earth's gravity is not the dominant governing factor on the dynamics of bodies in that domain, and other forces become more relevant. The study of thermodynamics investigates many of these domains, and reveals domains where phenomena such as inertia, friction, viscosity, and turbulence dominate. We do not have to descend to even microscopic scale to find other domains where the masses of objects are sufficiently small that their dynamics are easily dominated by electrostatic and electrodynamic phenomena. Thus, one does not have to look far before areas of application of the present research appear.

4.8.1 Implications for theories of telepresence

The present study forms part of a larger range of research approaches to issues of telepresence. Its results provide support for those who have suggested that where a proximal operator-robot interface accepts and produces informed control through representations, these representations must be specific to the task-relevant properties of the distal robot-environment interface (Draper, Kaber, & Usher, 1999; Mantovani & Riva, 1999).

To avoid collision during the alignment phases of the telerobotic manipulations performed in this experiment, the critical physical factors that needed to be controlled included distance to the target, misalignment of the end-effector and correct direction of rotation in order to correct for misalignments. In the experimental conditions that combined the mobile viewpoint and the self-referenced control frame, the critical physical factors were made directly available as first order optical variables, and there was one-to-one correspondence between the operator's control actions and the optical variables. This condition was also associated with superior performance in terms of a reduced number of collisions. This provides support for ecological approaches to perception-action which imply that real presence in teleoperation depends on aligning the information constraints in the operator's control interface with the action constraints of the distal real-world environment, and suggests that design of effective telepresence systems must be informed by theory of direct perception (Flach & Holden, 1998).

4.8.2 Implementation of an enhanced spaceborne telemanipulation system

There is good potential for implementation of telerobotic control on the space shuttle without excessive cost or technical challenge. A mobile viewpoint, as required for the egocentric virtual environment could be achieved with twin video cameras mounted stereoscopically on a pan/tilt base unit on the end of the manipulator arm. Motion of the cameras could be slaved to the head movements of an operator wearing a head-mounted display and “seated” at a control console. The operator would be free to turn his or her head and body to obtain a full spherical viewpoint (i.e. 360° both vertically and horizontally). The controls would always remain in a fixed position however (i.e. would not move with the movement of the operator’s body), in order to provide a consistent mapping of the “forward” direction with reference to the camera’s position on the manipulator arm.

4.9 Extensions and directions for further research

There are several possible manipulations of the present study that hold good potential for broadening and extending the results. Some have been mentioned above. Others not yet mentioned include: manipulation of body scaling in the virtual environment, increasing the duration of the training and testing phases, and additions of visual aids for control and navigation to the virtual environment.

4.9.1 Body-scaling

One factor of interest in the experiment is the effect of varying the scaling of the operator’s virtual body relative to the scale of the manipulator and manipulator environment. In a virtual environment, body scaling may be selected arbitrarily. In this experiment, the body-referenced scale factors were: scaling of hand controller translational movements to end-effector movements in the virtual environment (set at 1.5 m/s per 0.1 m of hand controller deflection), scaling of changes in head position (but not head orientation) to movement of the virtual viewpoint, (set at 1:1) and the stereo eye-separation distance and convergence distance (0.08 m and 12 m respectively). Uniform scaling up of these factors would effectively scale the entire virtual environment down, potentially changing the experimental tasks from what was effectively navigation through a virtual environment into a manipulation task performed entirely within virtual “arm’s reach”

Such an approach would be valuable in investigating further the high degree of interaction observed in the experiment between local parameters of the task and the optimal control interface for that task.

4.9.2 Experiment duration

The length of the training and testing phases in this experiment were brief, ranging between 15 – 20 minutes and 25 – 30 minutes respectively, per participant. Training of this duration possibly failed to control adequately for prior experience or for ongoing learning effects during the testing phase, introducing a greater degree of individual variation into the results than desirable. A comparable study (Park & Woldstad, 2000) had much more rigorous training, evaluation, and testing with a 90-min training session, followed by a 90-min training evaluation session, followed by up to 5 hrs of testing. Park and Woldstad required performance as measured by time to completion and error rate to meet a specified criteria of no more than ±10% variation for six consecutive trials, far more rigorous criteria than the rather loose requirements in the present experiment of a 3-min time limit on the second block of training. Lengthening the duration of training and testing in any follow up to the present study would ensure a greater degree of freedom from ongoing large-scale learning effects during the testing phase, and would reduce the variability between participants.

4.9.3 Additional visual aids

Although the present study used one visual aid to support participants’ perception of the linkage between the control frame of reference and the resultant effects upon the end-effector, further investigation of the effect on performance of such an aid is required.

4.10 Conclusion

The present experiment aimed to determine whether changing the control interface to a space telerobotic manipulation system to be based around an egocentric frame of reference would result in improved operator performance in a representative set of manipulation tasks. On the factor of control frame of reference, the egocentric self-referenced control frame offered superior performance in terms of the rate at which the task was completed. On the factor of viewpoint mobility, the egocentric frame's mobile viewpoint was inferior in terms of its support for rate of task completion and avoiding arm reach limit errors but was superior in its support for avoiding collisions between the arm and payload. The experiment thus provides support for partial application of an egocentric frame of reference to the telerobotic control of space-based articulated manipulators, A number of ways in which the performance decrements observed under the mobile viewpoint could be resolved were discussed, with a view to the possibility of more complete application.

❏

References

Bennett, K. M. B., Mucignat, C., Waterman, C., & Castiello, U. (1994). Vision and the reach to grasp movement. In K. M. B. Bennett & U. Castiello (Eds.), *Insights into the reach to grasp movement* (pp. 171-195). Amsterdam, Netherlands: North-Holland.

Brooks, F. P., Jr., Ouh-Young, M., Batter, J. J., & Kilpatrick, P. J. (1990). Project GROPE - Haptic displays for scientific visualization. *ACM Computer Graphics, 24*(4), 177-185.

Carr, K., & England, R. (Eds.). (1995). *Simulated and virtual realities: Elements of perception*. Philadelphia, PA: Taylor and Francis.

Draper, J. V., Kaber, D. B., & Usher, J. M. (1999). Speculations on the value of telepresence. *CyberPsychology and Behavior, 2*(4), 349-362.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*, 381-391.

Flach, J. M. (1990a). Control with an eye for perception: Precursors to an active psychophysics. *Ecological Psychology, 2*, 83-112.

Flach, J. M. (1990b). The ecology of human-machine systems I: Introduction. *Ecological Psychology, 2*, 191-205.

Flach, J. M., & Holden, J. G. (1998). The reality of experience. *Presence: Teleoperators and Virtual Environments, 7*, 90-95.

Gianaros, P. J., Muth, E. R., Mordkoff, J. T., Levine, M. X., & Stern, R. M. (2001). A questionnaire for the assessment of the multiple dimensions of motion sickness. *Aviation Space and Environmental Medicine, 72*(2), 115-119.

Holden, J. G., Flach, J. M., & Donchin, Y. (1999). Perceptual-motor coordination in an endoscopic surgery simulation. *Surgical Endoscopy, 13*, 127-132.

Kaufman, A. (1991). *Volume visualization*. Washington, DC: IEEE Computer Society Press.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology, 3*(3), 203-220.

Kennedy, R. S., Lanham, D. S., Massey, C. J., & Drexler, J. M. (1995). Gender differences in simulator sickness incidence: Implications for military virtual reality systems. *SAFE Journal, 25*(1), 69-76.

Lindberg, R. E., Longman, R. W., & Zedd, M. F. (1986, January 6-9). *Kinematics and reaction moment compensation for a spaceborne elbow manipulator.* Paper presented at the AIAA 24th Aerospace Sciences Meeting, (No. AIAA-86-0250), Reno, Nevada.

Lindberg, R. E., Longman, R. W., & Zedd, M. F. (1993). Kinematic and dynamic properties of an elbow manipulator mounted on a satellite. In Y. Xu & T. Kanade (Eds.), *Space robotics : Dynamics and control*. Boston, MA: Kluwer Academic Publishers.

Liu, A., Tharp, G., French, L., Lai, S., & Stark, L. (1993). Some of what one needs to know about using head-mounted displays in order to improve teleoperator performance. *IEEE Transactions on Robotics and Automation, 9*(5), 638-648.

Lumelsky, V. (1991). On human performance in telerobotics. *IEEE Transactions on Systems, Man, and Cybernetics, 21*(5), 971-982.

MacKenzie, I. S. (1992). Fitts' law as a research and design tool in human–computer interaction. *Human Computer Interaction, 7*(1), 91-139.

Mantovani, G., & Riva, G. (1999). "Real" presence: How different ontologies generate different criteria for presence, telepresence, and virtual presence. *Presence: Teleoperators and Virtual Environments, 8*(5), 540-550.

McCormick, E. P., Wickens, C. D., Banks, R., & Yeh, M. (1998). Frame of reference effects on scientific visualization subtasks. *Human Factors, 40*(3), 443-451.

Minsky, M. (1979, September). *Toward a remotely-manned energy and production economy* (No. A.I. Memo No. 544). Cambridge, MA: Massachusetts Institute of Technology Artificial Intelligence Laboratory.

Nguyen, P. K., & Hughes, P. C. (1994). Teleoperation: From the space shuttle to the space station. In S. B. Skaar & C. F. Ruoff (Eds.), *Teleoperation and robotics in space* (Vol. 161). Washington, DC: American Institute of Aeronautics and Astronautics.

Nordvik, H., & Amponsah, B. (1998). Gender differences in spatial abilities and spatial activity among university students in an egalitarian educational system. *Sex Roles, 38*(11-12), 1009-1023.

Olmos, O., Wickens, C. D., & Chudy, A. (2000). Tactical displays for combat awareness: An examination of dimensionality and frame of reference concepts and the application of cognitive engineering. *International Journal of Aviation Psychology, 10*(3), 247-271.

Owen, D. H. (1990). Perception and control of changes in self-motion: A functional approach to the study of information and skill. In R. Warren & A. H. Wertheim (Eds.), *Perception & control of self-motion* (pp. 289-326). Hillsdale, NJ: Erlbaum.

Park, S. H., & Woldstad, J. C. (2000). Multiple two-dimensional displays as an alternative to three-dimensional displays in telerobotic tasks. *Human Factors, 42*(4), 592-603.

Pressman, R. S. (2001). *Software engineering: A practitioner's approach* (5th ed.). Boston, MA: McGraw Hill.

Rheingold, H. (1991). *Virtual reality*. New York: Summit Books.

Ruoff, C. F. (1994). Overview of space telerobotics. In S. B. Skaar & C. F. Ruoff (Eds.), *Teleoperation and robotics in space* (Vol. 161). Washington, DC: American Institute of Aeronautics and Astronautics.

Schilling, R. J. (1990). *Fundamentals of robotics: Analysis and control*. Englewood Cliffs, NJ: Prentice-Hall.

Schneider, R. T. (1997). Simulation optimizes underwater robot arm design. *Hydraulics & Pneumatics, January 1997,* 12-14.

Sheridan, T. B. (1992). Musings on telepresence and virtual presence. *Presence: Teleoperators and Virtual Environments, 1*, 120-125.

Sheridan, T. B. (1994). Human enhancement and limitation in teleoperation. In S. B. Skaar & C. F. Ruoff (Eds.), *Teleoperation and robotics in space* (Vol. 161). Washington, DC: American Institute of Aeronautics and Astronautics.

Smith, R. L., & Stuart, M. A. (1993). The effects of spatially displaced visual feedback on remote manipulator performance. In *Crew interface analysis: Selected articles on space human factors research, 1987 - 1991* (pp. 104-110). Houston, TX: NASA, Johnson Space Center.

Soechting, J. F., Tong, D. C., & Flanders, M. (1996). Frames of reference in sensorimotor integration: Position sense of the arm and hand. In A. M. Wing, P. Haggard & J. R. Flanagan (Eds.), *Hand and brain: The neurophysiology and psychology of hand movements* (pp. 151-168). San Diego, CA: Academic Press.

Stumpf, H., & Eliot, J. (1995). Gender-related differences in spatial ability and the k factor of general spatial ability in a population of academically talented students. *Personality and Individual Differences, 19*(1), 33-45.

Vicente, K. J. (1995). A few implications of an ecological approach to human factors. In J. M. Flach, P. A. Hancock, J. K. Caird & K. J. Vicente (Eds.), *Global perspectives on the ecology of human-machine systems* (pp. 54-67). Hillsdale, New Jersey: Erlbaum.

Whitney, D. E. (1969). Resolved motion rate control of manipulators and human prostheses. *IEEE Transactions on Man-Machine Systems, 10*(2), 47-53.

Wickens, C. D. (1999). Frames of reference for navigation. In D. Gopher & A. Koriat (Eds.), *Attention and performance* (Vol. 16, pp. 113-144). Cambridge, MA: MIT Press.

Appendix A

Overview of the SRMS system

The space shuttle RMS is a remotely controlled anthropomorphic arm. The arm itself consists of two long slender booms, six motorised revolute joints, an end-effector and grapple for capture and manipulation of payloads, and swing-out mechanism and attachment point to the space shuttle longeron. There are one roll, two yaw, and three pitch joints arranged as illustrated in Figure 27. Once deployed alongside the shuttle's opened cargo bay, the SRMS possesses on overall length of approximately 15.3 metres.

Subject to the simultaneous requirements of minimal launch mass and a large operational workspace, the SRMS arm is of very lightweight construction and is quite flexible in comparison to typical terrestrial manipulators. In zero-gravity it is able to manipulate very large loads, up to a maximum 14515 kg (Nguyen & Hughes, 1994). On the ground however, it cannot lift even its own weight. For this reason, early SRMS operator training was

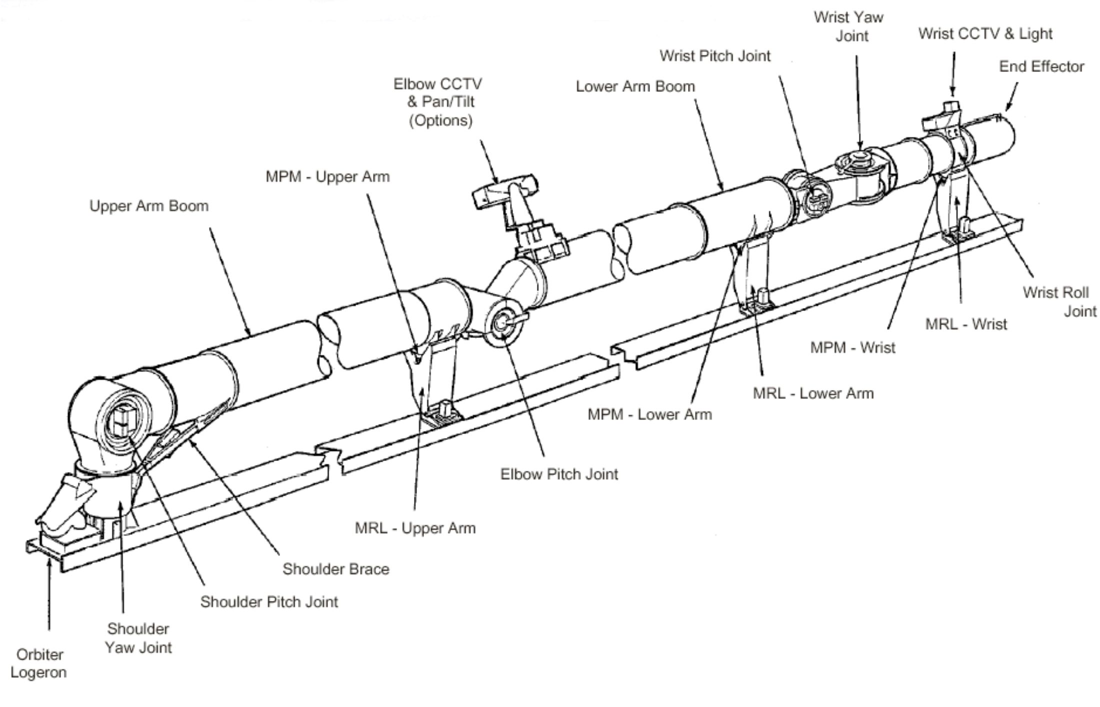


Figure 27. Schematic of SRMS architecture (courtesy M.D. Robotics).

performed using a lightweight balsa wood replica. Modern SRMS movement simulation uses a combination of computer simulation and a replica underwater robotic system, known as the Weightless Environment Training Facility RMS (WRMS) (Schneider, 1997).

The SRMS is operated from the aft flight deck of the space shuttle. The aft flight deck (Figure 28) is the somewhat cramped area at the rear of the upper space shuttle deck. The payload bay and SRMS workspace are viewable through two aft windows measuring 0.37m × 0.28m, as well as through two remotely controlled video cameras on the arm itself and four fixed video cameras mounted fore and aft in the payload bay on both starboard and port sides. Operations overhead are viewable through two slightly larger overhead windows in the aft flight deck. The SRMS operator is seated on an adjustable restraint in front of the operating console.

The SRMS uses a type of control, resolved motion rate control (Whitney, 1969), in which the operator specifies the desired rate of motion of the manipulator end-effector, and the individual joints of the arm are then moved to produce a motion corresponding as closely as possible, within the limits of the arm. The end-effector is translated by moving a three-axis hand controller. Software in the shuttle general-purpose computer reads the hand controller input and calculates and outputs the servo commands required to produce the corresponding arm translation. Changes in orientation of the end-effector are input through a second hand controller and are similarly processed. In addition, there are selector switches that allow the engagement of control modes for different loadings of the arm, the engagement of control modes where the joints may be manoeuvred individually, and control of the operation of the end-effector grapple and the video cameras mounted on the arm.

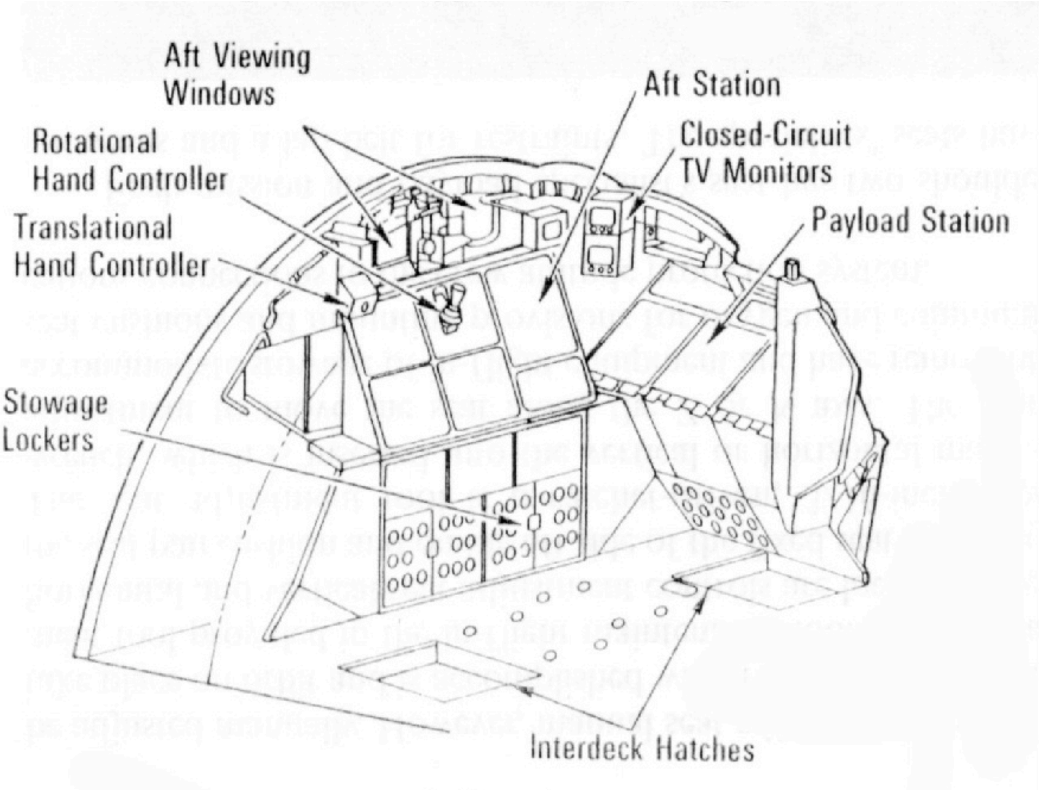


Figure 28. Space shuttle aft flight deck (courtesy NASA).

Appendix B

SRMS kinematics

The kinematic model of the SRMS arm used in the simulation is based on a discrete-time implementation of a resolved-motion rate control algorithm, in which motion of the end-effector is resolved into linear and rotational components. At each instant in time, the change in position and orientation of the end-effector is calculated and the arm's inverse kinematic transform used to compute the desired new joint angles at that instant.

The kinematics of the SRMS were analysed by the experimenter using procedures presented by Schilling (1990), with modifications from Lindberg, Longman and Zedd (1993), and are detailed below.

Assignment of kinematic parameters

Coordinate reference frames are assigned to the various parts of the manipulator thus:

1. The manipulator is considered to be made up of only joints and links. In the case of the SRMS there are 6 revolute joints (shoulder yaw, shoulder pitch, elbow pitch, wrist pitch, wrist yaw and wrist roll). Joint 1 connects the manipulator to the fixed base. Link 1 is attached beyond joint 1.
2. A coordinate reference frame designated ${}^{0}T$ is attached to the manipulator base, and defines a fixed coordinate system known as the *world coordinate system*.
3. A coordinate reference frame ${}^{n}T$ is attached at a point coincident with each joint n and moves with the joint. To simplify the kinematics for the particular case of the SRMS, the axes of these reference frames are arranged so that all axes are parallel when the arm is in the rest position, with the three pitch joints acting about their x axes, the two yaw joints acting about their y axes and the roll joint acting about its z axis.

4. For each joint n, the joint angle θ_n is defined to be the angle between the axis of link n – 1 and the axis of link n, measured in a right hand sense about the joint. The joint length d_n is defined to be the distance between joint n and joint n + 1, projected onto the axis of joint n.
5. For each link n, the link length a_n is defined to be the distance between joint n and joint n + 1, projected onto an axis perpendicular to the axis of joint n.
6. The last link, link n, is a pseudo-link connecting the body of the manipulator to the tool. Coordinate reference frame ^nT is attached to the tool, and defines a mobile coordinate system known as the *tool coordinate system*.
7. The axes of joints 1, 2 are coincident, and therefore the kinematics may be simplified by locating the origins of coordinate reference frames ^0T, ^1T and ^2T together at the shoulder joint, joint 2. Similarly, the axes of joints 5 and 6 are coincident and thus the origins of ^5T and ^6T are collocated at the wrist yaw joint, joint 5.

The reference frames of the complete manipulator appear in Figure 29. The values of the various parameters are listed in Table 3.

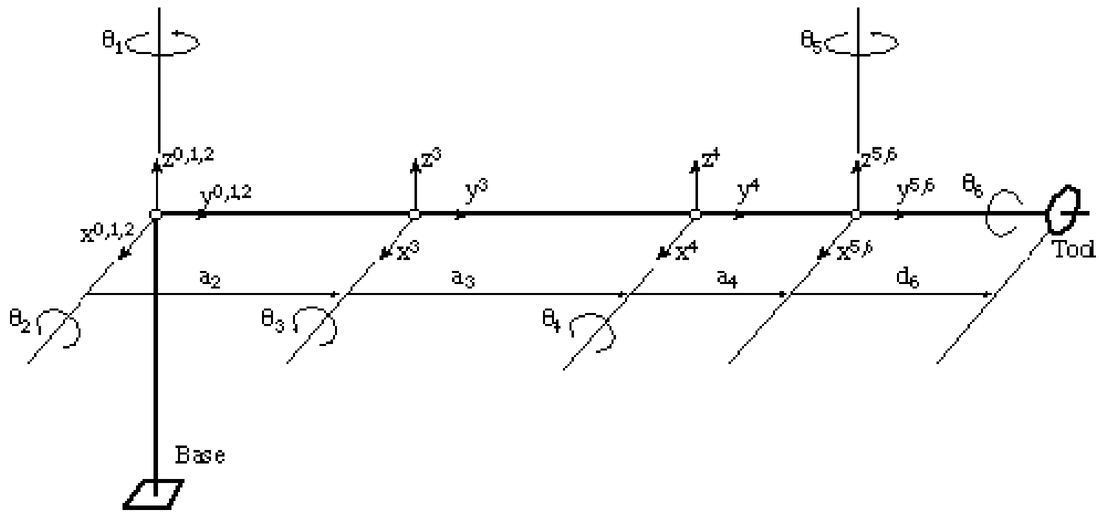


Figure 29. Coordinate reference frames of complete manipulator.

Table 3. Manipulator Kinematic Parameters.

Frame	Joint name	Joint home angle	Joint length (m)	Link name	Link length (m)
n		$\theta_n[0]$	d_n		a_n
1	shoulder yaw	0	0.3048	-	0
2	shoulder pitch	0	0	upper arm boom	$\sqrt{6.377^2 + 0.1524^2}$
3	elbow pitch	0	0	lower arm boom	$\sqrt{7.06^2 + 0.1524^2}$
4	wrist pitch	0	0	-	0.4572
5	wrist yaw	0	0	-	0
6	wrist roll	0	0.6604 + 0.762	-	0

Forward kinematics

Given the above assignment of coordinate reference frames, positions and orientations specified in one reference frame (e.g. ${}^{n}T$, the tool reference frame) can be transformed to a different reference frame (e.g. ${}^{0}T$, the base reference frame) using coordinate geometry. It is desirable to derive a transform such that given a set of joint angles, θ_1 thru θ_6, the position and orientation of the point of resolution (POR) of the tool may be specified relative to the base.

Expressing position and orientation using homogenous coordinate transforms, the point of resolution (POR) of the tool may be specified relative to the shoulder thus:

$$ {}^{0}_{6}\mathbf{T} = {}^{0}_{1}\mathbf{T}\,{}^{1}_{2}\mathbf{T}\,{}^{2}_{3}\mathbf{T}\,{}^{3}_{4}\mathbf{T}\,{}^{4}_{5}\mathbf{T}\,{}^{5}_{6}\mathbf{T} $$

$$
\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}
=
\begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\bullet
\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_2 & -S_2 & 0 \\ 0 & S_2 & C_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\bullet
\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_3 & -S_3 & a_2 \\ 0 & S_3 & C_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\bullet
$$

$$
\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_4 & -S_4 & a_3 \\ 0 & S_4 & C_4 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\bullet
\begin{bmatrix} C_5 & -S_5 & 0 & 0 \\ S_5 & C_5 & 0 & a_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\bullet
\begin{bmatrix} C_6 & 0 & S_6 & 0 \\ 0 & 1 & 0 & 0 \\ -S_6 & 0 & C_6 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\bullet
\begin{bmatrix} 1 & 0 & 0 & {}^{6}p_x \\ 0 & 1 & 0 & {}^{6}p_y \\ 0 & 0 & 1 & {}^{6}p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Where:

${}^{k-1}_{k}\mathbf{T}$ is the homogenous coordinate transform relating coordinates in coordinate system ${}^{k}\mathbf{P}$ to coordinates in coordinate system ${}^{k-1}\mathbf{P}$.

C_k and S_k are the cosine and sine of joint angle θ_k.

n, **o** and **a** are the normal, orthogonal and approach vectors (aligned with the x, y and z axes respectively) of the of the sixth coordinate frame attached to tool.

${}^{6}\mathbf{p}$ is the location of the tool expressed in the sixth coordinate system.

Multiplying out the right hand side of the above equation yields:

$$
\begin{aligned}
n_x &= C_1C_5C_6 - S_1(C_{234}S_5C_6 + S_{234}S_6) \\
n_y &= S_1C_5C_6 + C_1(C_{234}S_5C_6 + S_{234}S_6) \\
n_z &= S_{234}S_5C_6 - C_{234}S_6 \\
o_x &= -C_1S_5 - S_1C_{234}C_5 \\
o_y &= -S_1S_5 + C_1C_{234}C_5 \\
o_z &= S_{234}C_5 \\
a_x &= C_1C_5S_6 - S_1(C_{234}S_5S_6 - S_{234}C_6) \\
a_y &= S_1C_5S_6 + C_1(C_{234}S_5S_6 - S_{234}C_6) \\
a_z &= S_{234}S_5S_6 + C_{234}C_6 \\
p_x &= -S_1(C_2a_2 + C_{23}a_3 + C_{234}a_4) \\
p_y &= C_1(C_2a_2 + C_{23}a_3 + C_{234}a_4) \\
p_z &= S_2a_2 + S_{23}a_3 + S_{234}a_4
\end{aligned}
$$

Where the term C_{23} is shorthand for the cosine of $\theta_2 + \theta_3$, and similarly S_{23}, C_{234}, and S_{234}.

Inverse kinematics

The inverse kinematic transform (IKT) allows the determination of whether there exists a set of joint angles, θ_1 through θ_6, that satisfy a given position and orientation of the point of resolution (POR) of the tool.

Development of the IKT for the SRMS is complicated by the fact that the arm does not have a spherical wrist (i.e. the wrist pitch, yaw and roll joints are offset from each other). However, the development is simplified by the observation that the first five joints of the manipulator all lie in a single plane. It is further simplified by the kinematics assigned above, in which joints 1,2 and 3 and joints 5 and 6 were co-located.

Complete development of the IKT is presented in Lindberg, Longman and Zedd (1986). An algorithm was developed by the experimenter to determine the IKT and proceeds as follows.

1. The position of the POR is represented by the vector **p** expressed in coordinate reference frame ${}^0T$. Similarly, the orientation of the POR is represented by orthogonal unit vectors **n**, **o** and **a**, expressed in coordinate reference frame ${}^0T$. The location of the tool expressed in the sixth coordinate system is represented by the vector ${}^6\mathbf{p}$.
2. The position of the origin of the sixth coordinate frame is calculated by projection.

$${}_6\mathbf{p} = \mathbf{p} - \begin{bmatrix}\mathbf{n} & \mathbf{o} & \mathbf{a}\end{bmatrix} \bullet {}^6\mathbf{p}$$

3. The base yaw joint angle θ_1 is calculated directly.

$$\theta_1 = \operatorname{atan2}(-{}_6p_x, {}_6p_y)$$

   where atan2 represents a function computing a piecewise arctangent of two arguments, as implemented in the C programming language function atan2().
4. The "global tool pitch" angle $\theta_2 + \theta_3 + \theta_4$, representing the pitch angle of the tool relative to the base x–y plane, is calculated.

$$\theta_{234} = \operatorname{atan2}(o_z, -o_x S_1 + o_Y C_1)$$

where S_1 and C_1 are the sine and cosine respectively of θ_1.calculated in the previous step.

5. p_u and p_v are the projection in the vertical plane of links 2 and 3 onto an axis parallel to link 4, and the projection in the vertical plane of links 2 and 3 onto an axis perpendicular to link 4, respectively.

$$p_u = -C_{234}(S_1 \, {}^{\cdot}_{6} p_x - C_1 \, {}^{\cdot}_{6} p_x) + S_{234} \, {}^{\cdot}_{6} p_z - a_4$$
$$p_v = -S_{234}(S_1 \, {}^{\cdot}_{6} p_x - C_1 \, {}^{\cdot}_{6} p_x) - C_{234} \, {}^{\cdot}_{6} p_z$$

6. Given θ_{234} and p_u and p_v, the cosine of θ_3, denoted C_3, is given by:

$$C_3 = \frac{p_u^2 + p_v^2 - a_2^2 - a_3^2}{2a_2a_3}$$

If the value of the right hand side of the above equation lies outside the range [–1.0, 1.0], then the inverse of C_3 is undefined, no solution exists to the inverse kinematic problem, and the algorithm is terminated. These cases are those in which the specified position and orientation of the POR lies outside the envelope of points reachable by the manipulator. If however, the right hand side lies within the range [–1.0, 1.0], then θ_3 is given by:

$$\theta_3 = \pm \arccos(C_3)$$

The positive and negative solutions to this equation may be characterised as the "elbow up" and "elbow down" solutions respectively. In the SRMS, elbow up solutions are not possible so the negative solution is discarded and the solution is sufficiently constrained to produce a unique solution to the IKT.

7. With θ_3 known, the wrist pitch angle is uniquely determined and is given by:

$$\theta_4 = \operatorname{atan2}\left(-a_2S_3p_u + (a_2C_3 + a_3)p_v, (a_2C_3 + a_3)p_u + a_2S_3p_v\right)$$

and the shoulder pitch angle may be obtained by subtraction:

$$\theta_2 = \theta_{234} - \theta_3 - \theta_4$$

8. With determination of the position of all frames complete at this point, the final step in the IKT algorithm is to calculate the wrist pitch and yaw joint angles from the three tool orientation vectors:

$$\theta_5 = \operatorname{atan2}\left(-C_1 o_x - S_1 o_y, C_{234}(-S_1 o_x + C_1 o_y) + S_{234} o_z\right)$$
$$\theta_6 = \operatorname{atan2}\left(-S_{234}(S_1 n_x - C_1 n_y) - C_{234} n_z, S_{234}(S_1 a_x - C_1 a_y) - C_{234} a_z\right)$$

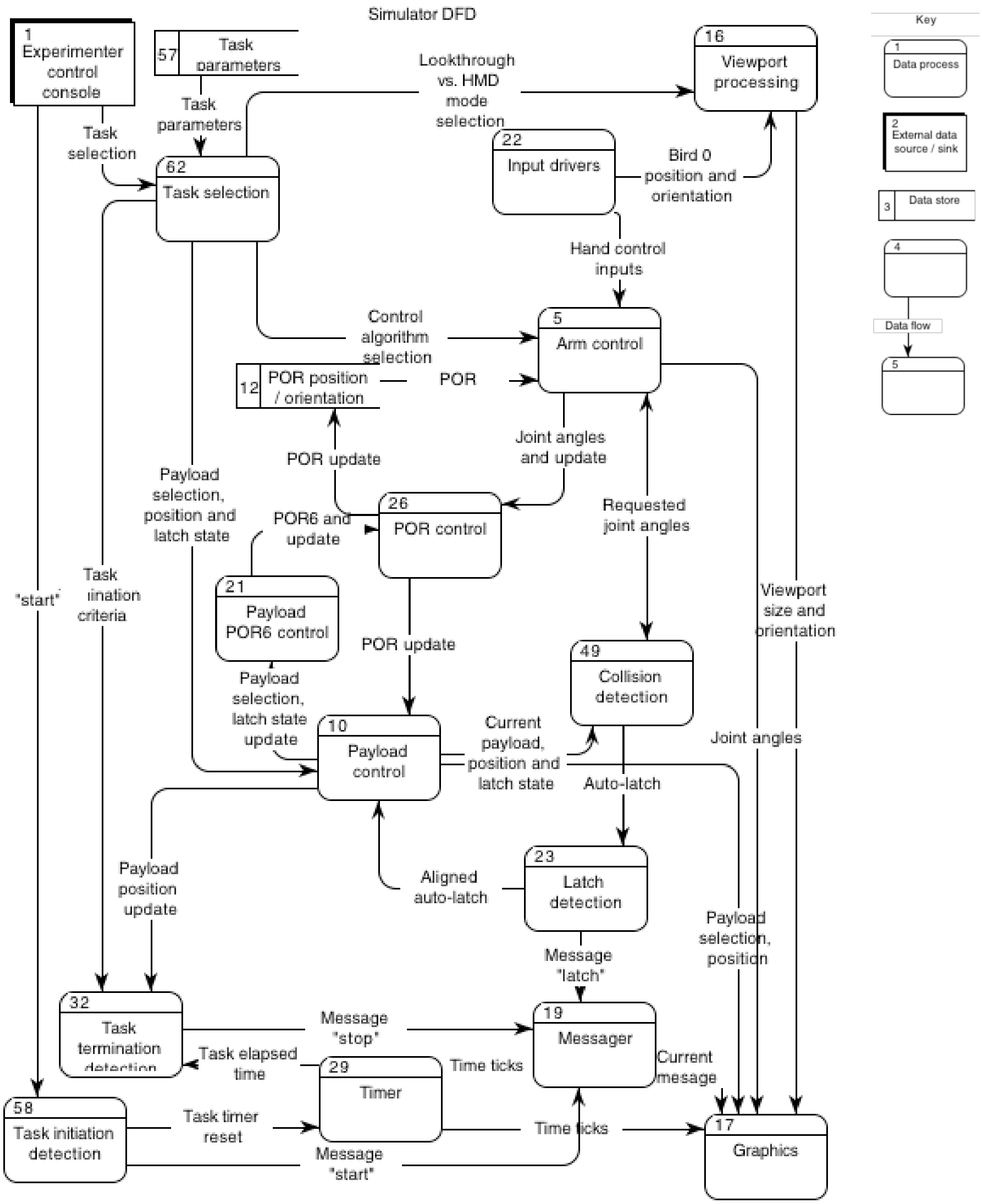
Any solution to the IKT may be further constrained by the allowable range of travel for each joint, the so-called joint soft limits.

❑

Appendix C

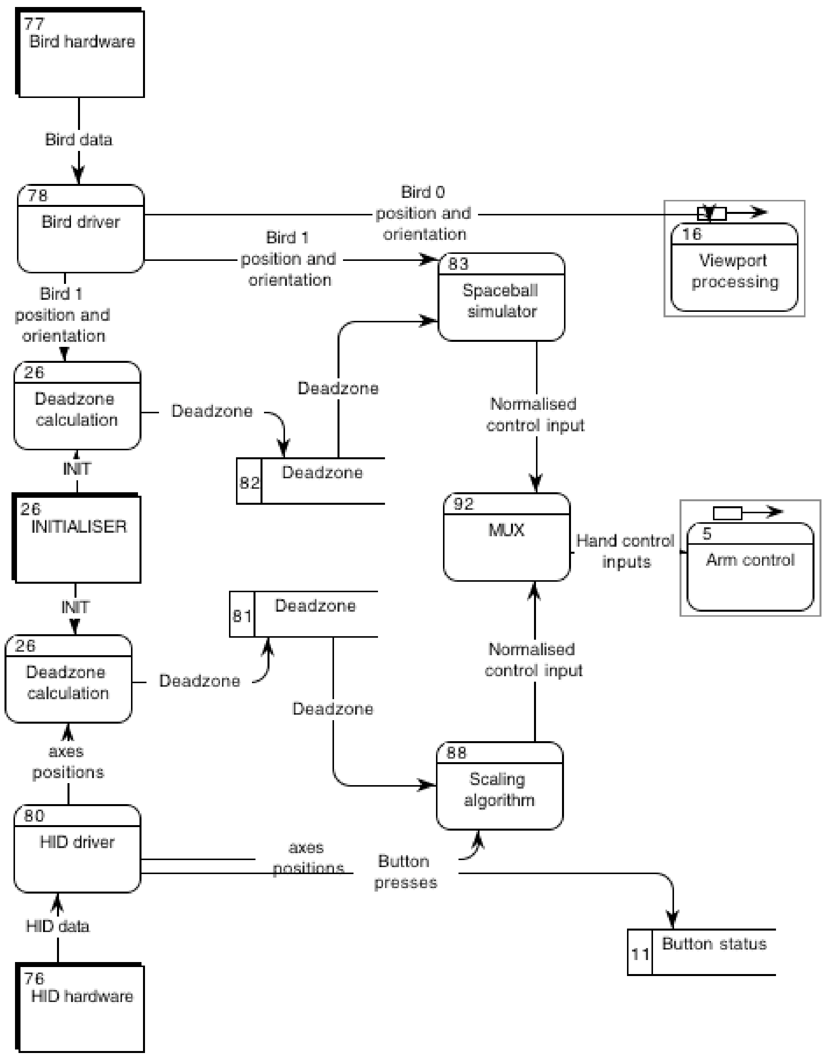
Data flow diagrams

The diagrams below represent the flow of data through the simulator software, following the methodology developed by Pressman (2001).

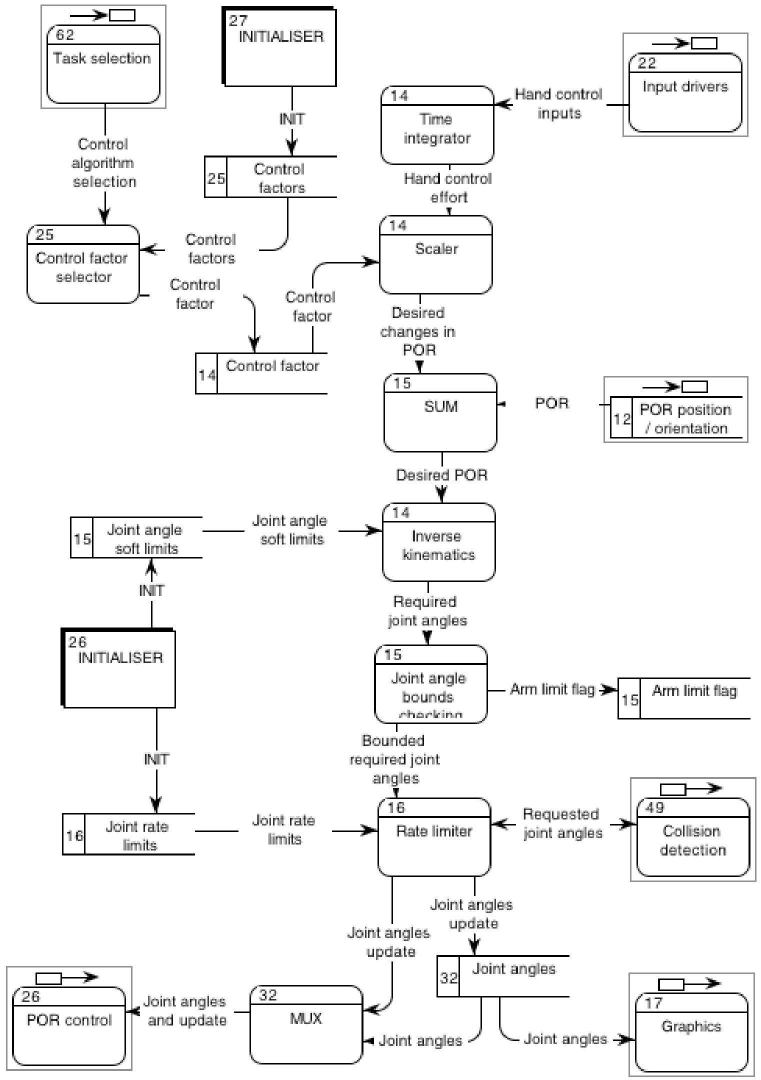


10

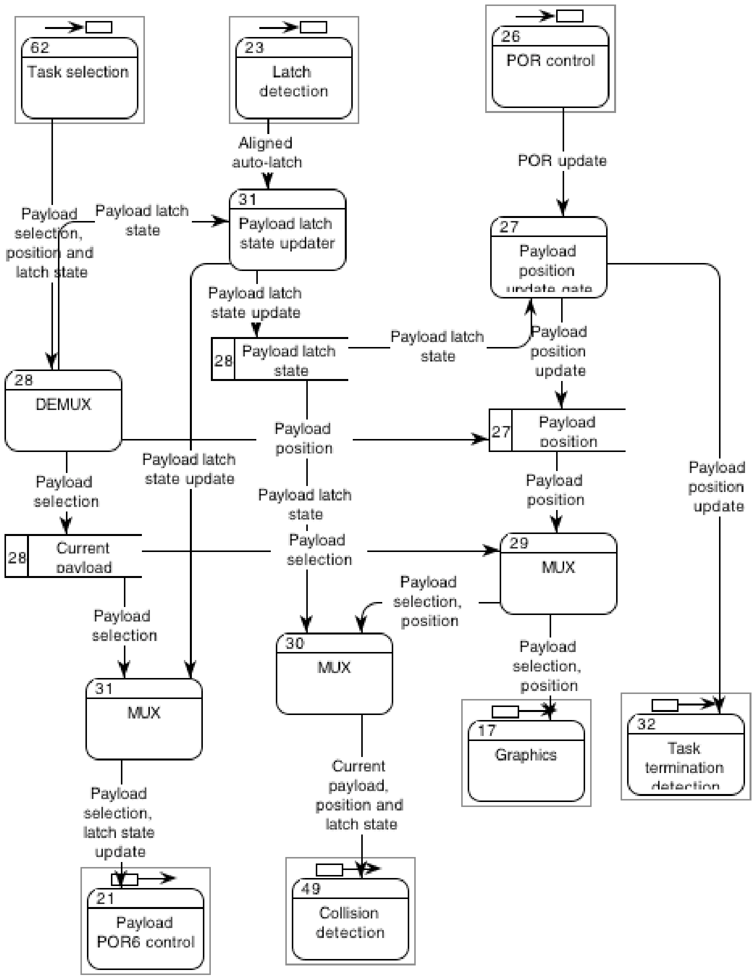
Simulator DFD : Input drivers



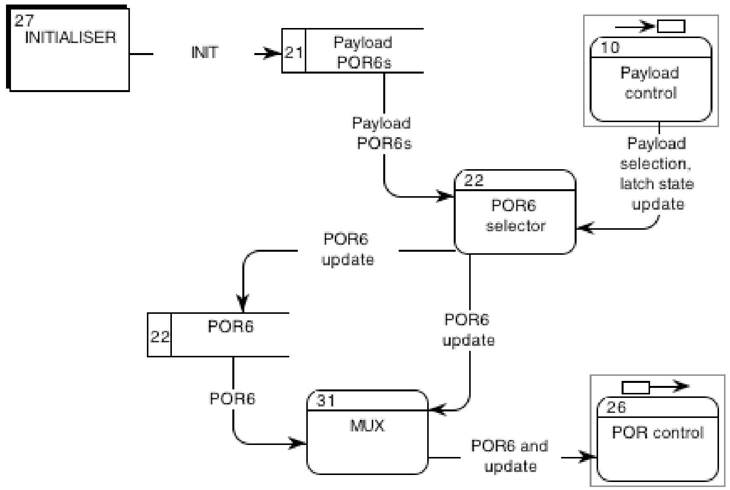
Simulator DFD : Arm control



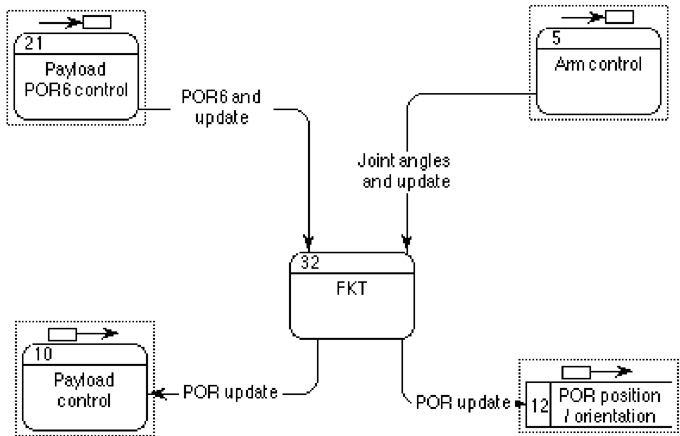
Simulator DFD : Payload control

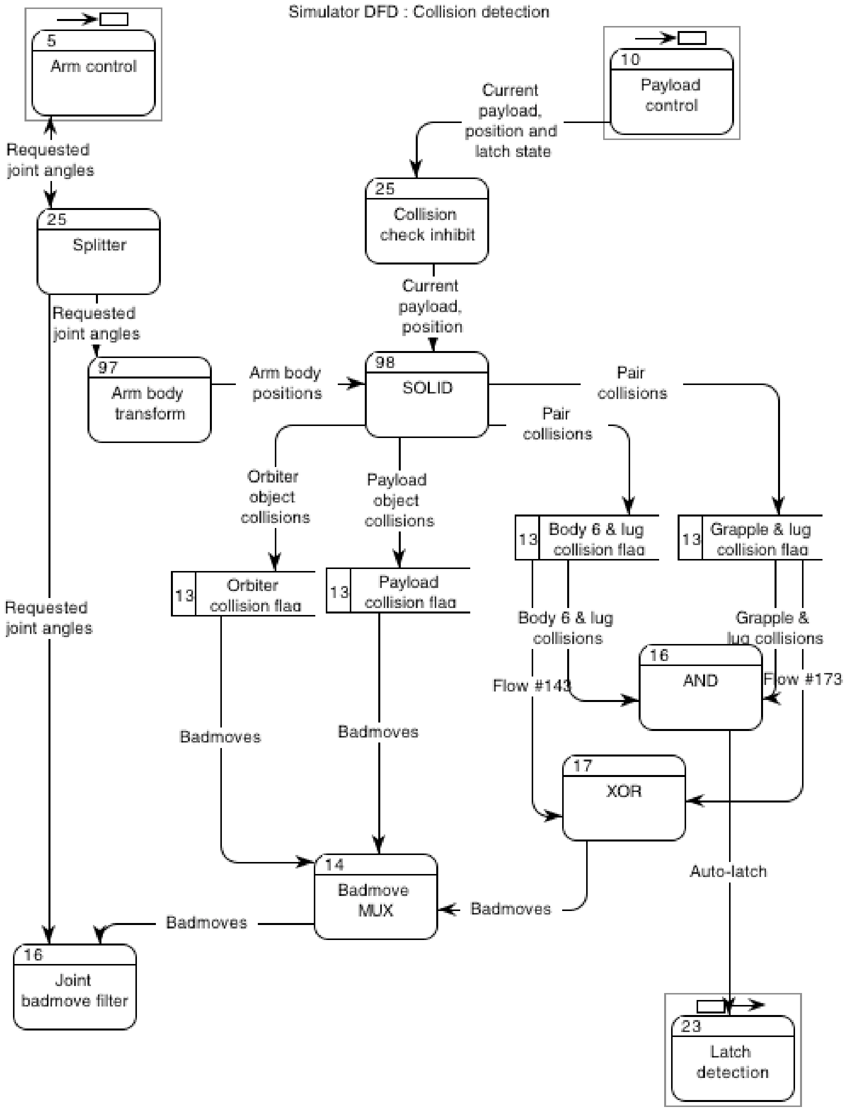


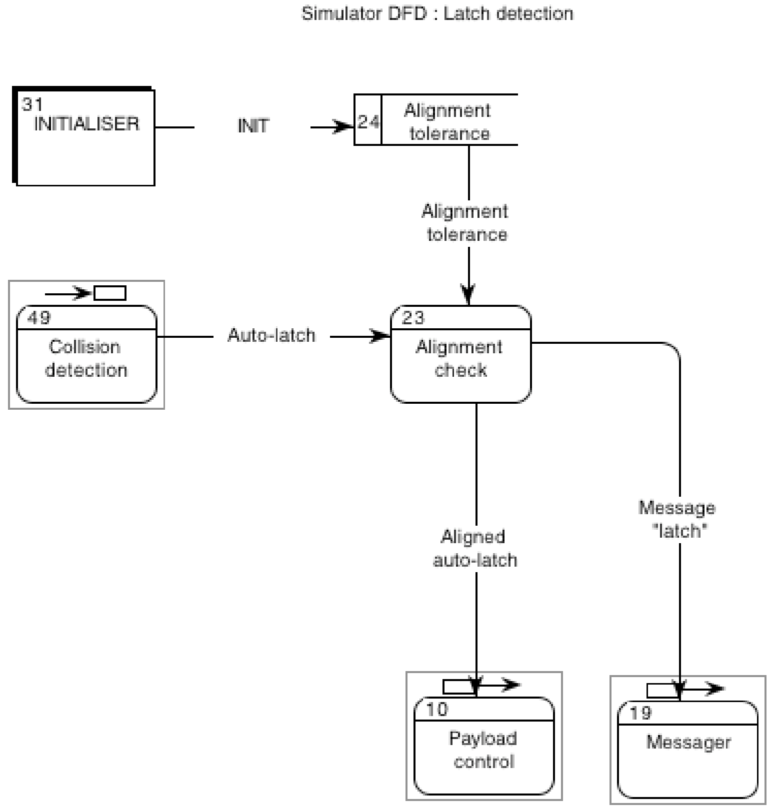
Simulator DFD : Payload POR6 control



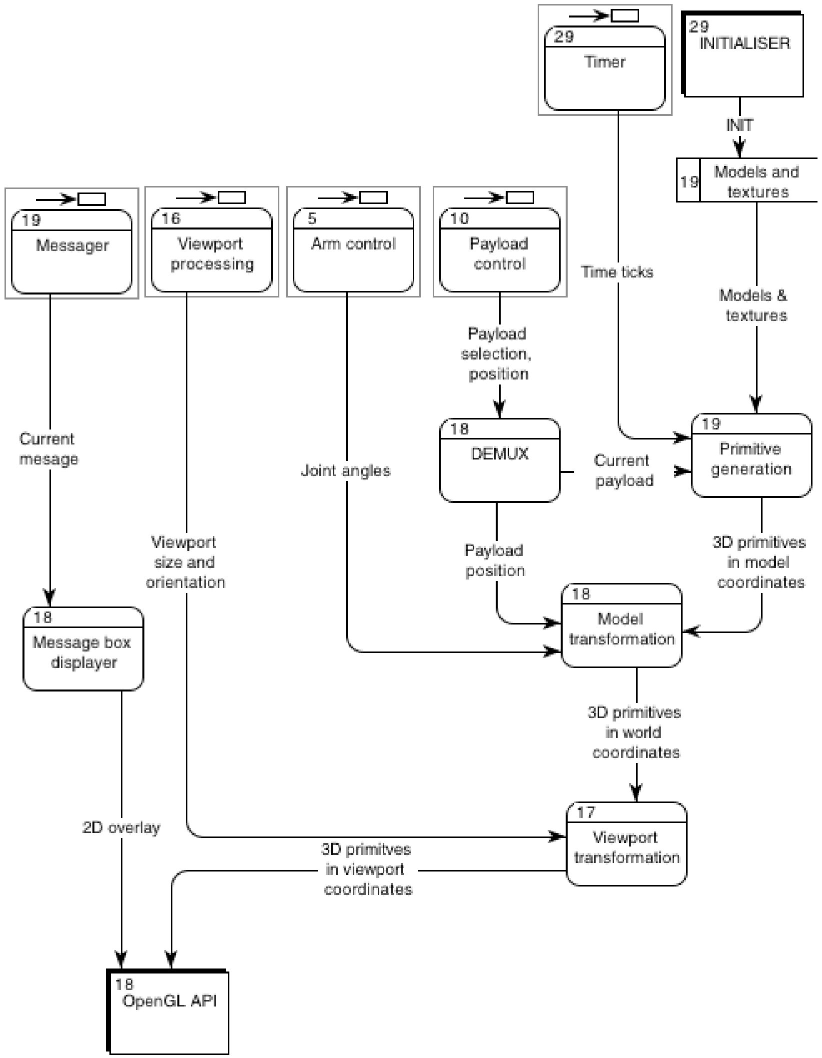
Simulator DFD : POR control



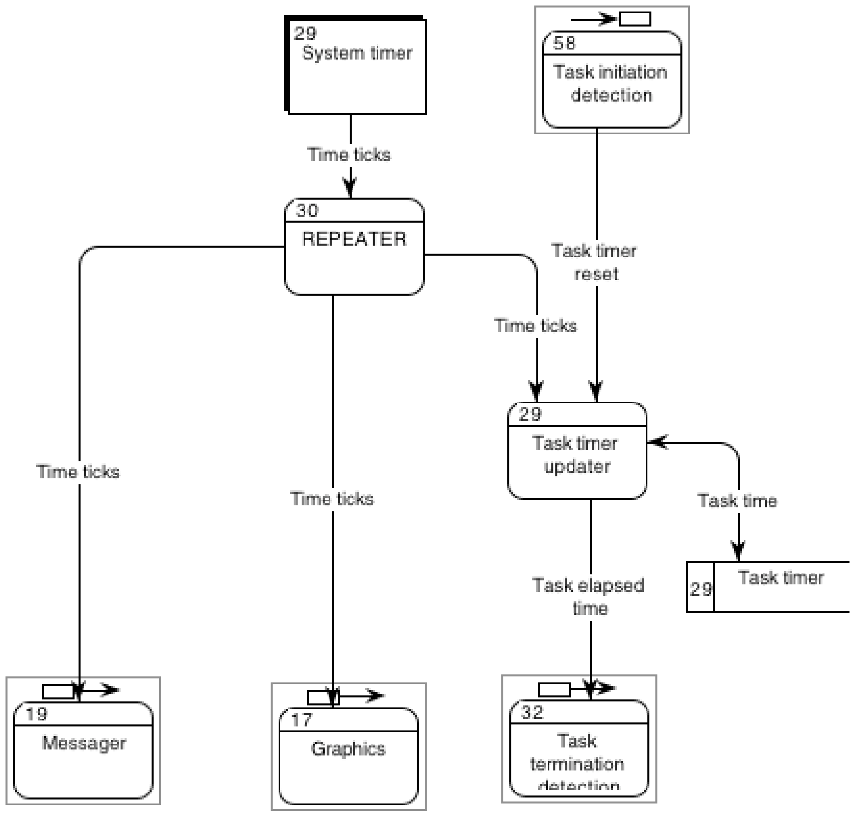

Simulator DFD : Collision detection
5
Arm control
Requested joint angles
25
Splitter
Requested joint angles
97
Arm body transform
Arm body positions
10
Payload control
Current payload, position and latch state
25
Collision check inhibit
Current payload, position
98
SOLID
Pair collisions
Pair collisions
Orbiter object collisions
Payload object collisions
13
Orbiter collision flag
13
Payload collision flag
13
Body 6 & lug collision flag
13
Grapple & lug collision flag
Body 6 & lug collisions
Grapple & lug collisions
Flow #143
Flow #173
16
AND
17
XOR
Requested joint angles
Badmoves
Badmoves
14
Badmove MUX
Badmoves
Badmoves
Auto-latch
16
Joint badmove filter
23
Latch detection


Simulator DFD : Latch detection
31
INITIALISER
INIT
24
Alignment tolerance
Alignment tolerance
49
Collision detection
Auto-latch
23
Alignment check
Aligned auto-latch
Message "latch"
10
Payload control
19
Messager

Simulator DFD : Graphics



Simulator DFD : Timer



Appendix D

Human performance in space telerobotic manipulation

Participant information

The experiment you are about to participate in is investigating the performance of humans operating robots at remote locations via telecommunications links. In particular, it will investigate the effects of varying certain aspects of the human-robot interface on the speed and accuracy in performing manipulation tasks.

You will be instructed in the use of a virtual reality headset and hand controllers and will be trained for approximately 15 minutes to control a robot arm to perform simple manipulation tasks. Should you successfully complete the training, following a break you will be required to perform another series of manipulation tasks, requiring approximately 20 to 30 minutes.

Important: Use of a virtual reality simulator can induce symptoms similar to motion sickness. This syndrome of effects, known as simulator sickness, can include general discomfort, fatigue, headache, eyestrain, nausea, blurred vision and dizziness. It does not affect everyone, and varies with the situation simulated. When it does occur, it usually ceases within a minute or so once exposure to the simulation is stopped. If you experience physical discomfort while in the simulator such that you do not feel you can continue, please advise the experimenter immediately and the simulation will cease. If you experience mild physical discomfort but feel you can continue, please also advise the experimenter of this.

All information and data collected in this study are kept private and confidential to the experimenter and the experimenter's supervisor. Individual participants will not be identifiable in results or publications. Your participation in this study is optional and you may withdraw your participation at any time, including the withdrawal of any information you have provided. However, by signing the consent form attached, it is understood that you have consented to participate in this experiment and to publication of the results, with the understanding that anonymity will be preserved.

If you have questions related to the study itself or the results obtained from your participation, please feel free to contact Philip Lamb, Department of Psychology, University of Canterbury, in Room 605, by phone at 364-2987 ext 7173, or by email at prl24@student.canterbury.ac.nz.

This research has been reviewed and approved by the University of Canterbury Human Ethics Committee.

Please take this sheet with you when you leave.

Human performance in space telerobotic manipulation

General demographics

Please circle the appropriate answer or fill in the spaces provided:

1. Sex: M / F
2. Age: _______
3. Handedness: Left / Right
4. Simulator experience:

   "Simulator" includes full-motion simulators, head-slaved virtual reality equipment, and 3D first-person perspective computer games including flight simulators, "Quake" and "Tomb Raider" style games, and "Descent" style space flight simulations.

   None.
   Less than 5 hours.
   5 – 50 hours
   50 – 500 hours
   More than 500 hours

Participant consent

- I have read the participant information sheet provided and understand the description of the above-named experiment.
- On this basis, I agree to participate as a subject in the experiment, and I consent to publication of the results, with the understanding that anonymity will be preserved.
- I understand that I may withdraw my participation at any time, including the withdrawal of any information I have provided.

Name:..

Signed: .... Date:...

Student ID:..

Pre-experiment simulator sickness questionnaire

In order to ensure your physical well-being following exposure to the simulator, it is necessary to enquire as to your present state of health. A similar questionnaire will be given to you following the experiment.

Please indicate the degree to which you are experiencing the following symptoms ***right now.***

General discomfort	*None*	*Slight*	*Moderate*	*Severe*
Fatigue	*None*	*Slight*	*Moderate*	*Severe*
Headache	*None*	*Slight*	*Moderate*	*Severe*
Eyestrain	*None*	*Slight*	*Moderate*	*Severe*
Difficulty focusing	*None*	*Slight*	*Moderate*	*Severe*
Increased salivation	*None*	*Slight*	*Moderate*	*Severe*
Sweating	*None*	*Slight*	*Moderate*	*Severe*
Nausea	*None*	*Slight*	*Moderate*	*Severe*
Difficulty concentrating	*None*	*Slight*	*Moderate*	*Severe*
Fullness of head [1]	*None*	*Slight*	*Moderate*	*Severe*
Blurred vision	*None*	*Slight*	*Moderate*	*Severe*
Dizzy (eyes open)	*None*	*Slight*	*Moderate*	*Severe*
Dizzy (eyes closed)	*None*	*Slight*	*Moderate*	*Severe*
Vertigo [2]	*None*	*Slight*	*Moderate*	*Severe*
Stomach awareness	*None*	*Slight*	*Moderate*	*Severe*
Burping	*None*	*Slight*	*Moderate*	*Severe*

[1] Fullness of head refers to an awareness of pressure in the head.
[2] Vertigo refers to a loss of orientation with respect to vertical or upright.

Are you currently experiencing any ailment or other condition outside your normal state of health that might account for any of these symptoms?

Yes *No*

If yes, please indicate briefly the nature of the condition or ailment:

Thank you for your participation and cooperation.

Philip Lamb.

Participant code	*Date*	*1*	*2*	*3*	*4*

Post-experiment simulator sickness questionnaire

In order to ensure your physical well-being following exposure to the simulator, please complete the following questionnaire now.

Please indicate the degree to which you are experiencing the following symptoms ***right now.***

General discomfort	*None*	*Slight*	*Moderate*	*Severe*
Fatigue	*None*	*Slight*	*Moderate*	*Severe*
Headache	*None*	*Slight*	*Moderate*	*Severe*
Eyestrain	*None*	*Slight*	*Moderate*	*Severe*
Difficulty focusing	*None*	*Slight*	*Moderate*	*Severe*
Increased salivation	*None*	*Slight*	*Moderate*	*Severe*
Sweating	*None*	*Slight*	*Moderate*	*Severe*
Nausea	*None*	*Slight*	*Moderate*	*Severe*
Difficulty concentrating	*None*	*Slight*	*Moderate*	*Severe*
Fullness of head [1]	*None*	*Slight*	*Moderate*	*Severe*
Blurred vision	*None*	*Slight*	*Moderate*	*Severe*
Dizzy (eyes open)	*None*	*Slight*	*Moderate*	*Severe*
Dizzy (eyes closed)	*None*	*Slight*	*Moderate*	*Severe*
Vertigo [2]	*None*	*Slight*	*Moderate*	*Severe*
Stomach awareness	*None*	*Slight*	*Moderate*	*Severe*
Burping	*None*	*Slight*	*Moderate*	*Severe*

[1] Fullness of head refers to an awareness of pressure in the head.
[2] Vertigo refers to a loss of orientation with respect to vertical or upright.

Thank you for your participation and cooperation.

Philip Lamb.

Participant code	*Date*	*1*	*2*	*3*	*4*

Take-home simulator sickness questionnaire

In order to ensure your physical well-being following exposure to the simulator, please complete the following questionnaire in 3 to 12 hours time, and return it to the Department of Psychology Office on Level 2 or alternately fold, seal and return it freepost by standard mail.

Please indicate the degree to which you are experiencing the following symptoms ***right now.***

General discomfort	*None*	*Slight*	*Moderate*	*Severe*
Fatigue	*None*	*Slight*	*Moderate*	*Severe*
Headache	*None*	*Slight*	*Moderate*	*Severe*
Eyestrain	*None*	*Slight*	*Moderate*	*Severe*
Difficulty focusing	*None*	*Slight*	*Moderate*	*Severe*
Increased salivation	*None*	*Slight*	*Moderate*	*Severe*
Sweating	*None*	*Slight*	*Moderate*	*Severe*
Nausea	*None*	*Slight*	*Moderate*	*Severe*
Difficulty concentrating	*None*	*Slight*	*Moderate*	*Severe*
Fullness of head [1]	*None*	*Slight*	*Moderate*	*Severe*
Blurred vision	*None*	*Slight*	*Moderate*	*Severe*
Dizzy (eyes open)	*None*	*Slight*	*Moderate*	*Severe*
Dizzy (eyes closed)	*None*	*Slight*	*Moderate*	*Severe*
Vertigo [2]	*None*	*Slight*	*Moderate*	*Severe*
Stomach awareness	*None*	*Slight*	*Moderate*	*Severe*
Burping	*None*	*Slight*	*Moderate*	*Severe*

[1] Fullness of head refers to an awareness of pressure in the head.
[2] Vertigo refers to a loss of orientation with respect to vertical or upright.

Have you participated in any activity since participating in the experiment that might account for any of these symptoms – e.g. exercise, public speaking, video games etc.?

Yes *No*

If yes, please indicate briefly the nature of the activity:

Thank you for your participation and cooperation.

Philip Lamb.

Participant code	*Date*	*1*	*2*	*3*	*4*

Appendix E

Detail of selected statistical analyses

Table 4. ANOVA for Task Completion Rate (§3.2.2, p35)

Source	SS	d.f.	MS	F	p
Task 1					
Between participants					
Intercept	0.297826	1	0.297826	509.8	.000**
Error	0.021615	37	0.000584		
Within participants					
VIEWFOR	0.000048	1	0.000048	0.306	.583
Error	0.005782	37	0.000156		
CTRLFOR	0.001650	1	0.001650	9.352	.0041**
Error	0.006529	37	0.000176		
VIEWFOR*CTRLFOR	0.000574	1	0.000574	3.641	.0642†
Error	0.005837	37	0.000158		
Task 2					
Between participants					
Intercept	0.091523	1	0.091523	419.8	.000**
Error	0.008066	37	0.000218		
Within participants					
VIEWFOR	0.003222	1	0.003222	55.71	.000**
Error	0.002140	37	0.000058		
CTRLFOR	0.000547	1	0.000547	12.43	.0011**
Error	0.001628	37	0.000044		
VIEWFOR*CTRLFOR	0.001237	1	0.001237	21.95	.000**
Error	0.002085	37	0.000056		
Task 3					
Between participants					
Intercept	0.045921	1	0.045921	273.5	.000**
Error	0.006211	37	0.000168		
Within participants					
VIEWFOR	0.002047	1	0.002047	36.51	.000**
Error	0.002074	37	0.000056		
CTRLFOR	0.000604	1	0.000604	10.21	.0029**
Error	0.002189	37	0.000059		
VIEWFOR*CTRLFOR	0.000091	1	0.000091	1.676	.204
Error	0.002013	37	0.000054		

Note: ** p < .01, * p < .05, † p < .10.

Table 5. ANOVA for ratio of Completion Rate pre-latch to post latch (§3.2.4, p40).

Source	SS	d.f.	MS	F	p
			Task 1		
Between participants					
Intercept	275.7289	1	275.7289	351.5	.000**
Error	28.2365	36	0.7843		
Within participants					
VIEWFOR	1.2436	1	1.2436	4.52	.040*
Error	9.8950	36	0.2749		
CTRLFOR	1.0997	1	1.0997	2.69	.110
Error	14.7257	36	0.4090		
VIEWFOR*CTRLFOR	0.8910	1	0.8910	2.93	.095†
Error	10.9384	36	0.3038		
			Task 2		
Between participants					
Intercept	369.9266	1	369.9266	293.4	.000**
Error	37.8199	30	1.2607		
Within participants					
VIEWFOR	0.0037	1	0.0037	0.0058	.940
Error	19.4108	30	0.6470		
CTRLFOR	5.9393	1	5.9393	5.66	.024*
Error	31.4795	30	1.0493		
VIEWFOR*CTRLFOR	15.0115	1	15.0115	19.79	.000**
Error	22.7563	30	0.7585		
			Task 3		
Between participants					
Intercept	209.5697	1	209.5697	157.8	.000**
Error	27.8979	21	1.3285		
Within participants					
VIEWFOR	13.2957	1	13.2957	10.62	.004**
Error	26.2986	21	1.2523		
CTRLFOR	0.1027	1	0.1027	0.099	.757
Error	21.8894	21	1.0424		
VIEWFOR*CTRLFOR	1.2259	1	1.2259	1.10	.306
Error	23.4294	21	1.1157		

Note: ** p < .01, * p < .05, † p < .10.

Table 6. ANOVA for $\log_e$ of total head movement (§3.5, p50).

	SS	d.f.	MS	F	p
Between participants					
Intercept	529.2	1	529.2	458.1903	.000**
Error	42.7	37	1.16		
Within participants					
TASK	147.4	2	73.7	303.0549	.000**
Error	18.00	74	0.243		
VIEWFOR	116.0	1	116.0	851.0701	.000**
Error	5.04	37	0.1363		
CTRLFOR	0.485	1	0.4850	2.4902	0.123
Error	7.21	37	0.1948		
TASK*VIEWFOR	2.32	2	1.1608	6.0423	.0037**
Error	14.22	74	0.1921		
TASK*CTRLFOR	0.0865	2	0.0433	0.2413	.786
Error	13.26	74	0.1792		
VIEWFOR*CTRLFOR	0.0496	1	0.0496	0.3547	.555
Error	5.18	37	0.1400		
TASK*VIEWFOR*CTRLFOR	0.174	2	0.0868	0.6954	.502
Error	9.24	74	0.1248		

Note: ** p < .01, * p < .05, † p < .10.

Table 7. ANOVA for total hand controller work (§3.6, p52).

Source	SS	d.f.	MS	F	p
Between participants					
Intercept	805739.	1	805739	771.4829	.000**
Error	38643	37	1044		
Within participants					
TASK	73226	2	3661	152.2809	.000**
Error	17792	74	240.4		
VIEWFOR	3100	1	3100	20.7550	.000**
Error	5527	37	149.4		
CTRLFOR	712	1	713	5.6981	.022*
Error	4628	37	125.1		
TASK*VIEWFOR	1810	2	905	7.3447	.0012**
Error	9121	74	123.3		
TASK*CTRLFOR	106.9	2	53.5	0.5597	.574
Error	7068	74	95.5		
VIEWFOR*CTRLFOR	18.6	1	18.6	0.2129	.647
Error	3224	37	87.1		
TASK*VIEWFOR*CTRLFOR	1208	2	604	5.1820	.0078
Error	8631	74	116.6		

Note: ** p < .01, * p < .05, † p < .10.

Glossary

Selected definitions of terms and abbreviations, as used in the text, appear below; where possible usage coincides with that found in other sources.

Actual: The physically tangible referent of an object or quality represented in a computer-generated environment (as in *actual body position*). (See also: virtual.)

Astronaut: A person who leaves Earth's orbit. (See also: EVA.)

API: *Applications Programming Interface*. A set of documented entry points to a pre-packaged software library, which taken together provide a well-defined set of related functions for use by software applications.

Complex sociotechnical system: A term coined by Jens Rasmussen to describe systems where human operators control and supervise automated technology in order to accomplish work, and where the system is of sufficient scale and complexity that control requires coordination between multiple operators.

Egocentric: Centred about or expressed relative to the observer. (See also: Exocentric, frame of reference.)

EVA: *Extra vehicular activities*. Activities conducted outside a space vehicle. Also used in adjective form to distinguish persons and objects outside the space vehicle from those within (as in *EVA astronaut*).

Exocentric: Centred about or expressed relative to an object fixed in the environment and external to the observer. (See also: Egocentric, frame of reference.)

FKT: *Forward kinematic transform*. A set of mathematical equations that allow the calculation of a robot arm's position in Cartesian coordinates given the arm's joint angles.

Frame of reference: A coordinate system whose properties are defined in terms of properties of the object to which it is attached. Typically, for a given space, many frames of reference may be arbitrarily defined.

IKT: *Inverse kinematic transform*. A set of mathematical equations which, for a given position of a robot arm in Cartesian coordinates, may produce a set of joint angles that satisfy that position.

Longeron: The sill of the space shuttle cargo bay, mounting point for the swing-out mechanism to which the SRMS arm is attached.

POR: *Point of resolution.* A matrix representation of the position and orientation of a point, about which control actions upon a robot arm are expressed. For an unladen robot arm, the POR typically describes the position and orientation of the tip of the robot's arm or attached tool. When the arm is carrying a payload however, the POR generally describes a point upon the payload, usually the payload's centroid.

RMS: *Remote manipulator system*. Generic name for a manipulator used for performing tasks at a location remote to the operator. (See also: SRMS, SSRMS.)

STS: *Space Transportation System*. NASA's name for its space vehicle commonly known as the space shuttle and including flight hardware such as external tanks and solid rocket boosters.

SRMS: *Space shuttle remote manipulator system*. The official name for the Canadarm robotic manipulator on the space shuttle.

SSRMS: *Space station remote manipulator system*. The official name for the primary robotic manipulator on the International Space Station.

Teleoperation: The performance of tasks at a remote site by an operator at a local site, where control commands and feedback travel via telecommunication links.

Telepresence: A term coined by Howard Rheingold, referring to the phenomenal experience of being physically present at a remote location.

Telerobotic manipulation system: A system for performing manipulation tasks using a teleoperated robot. (See: Teleoperation.)

Virtual: A computer generated object or quality, which a human operator may observe and/or interact with, and which may or may not have a physically tangible correlate (as in *virtual body position*). (See also: actual.)

❏