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.

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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

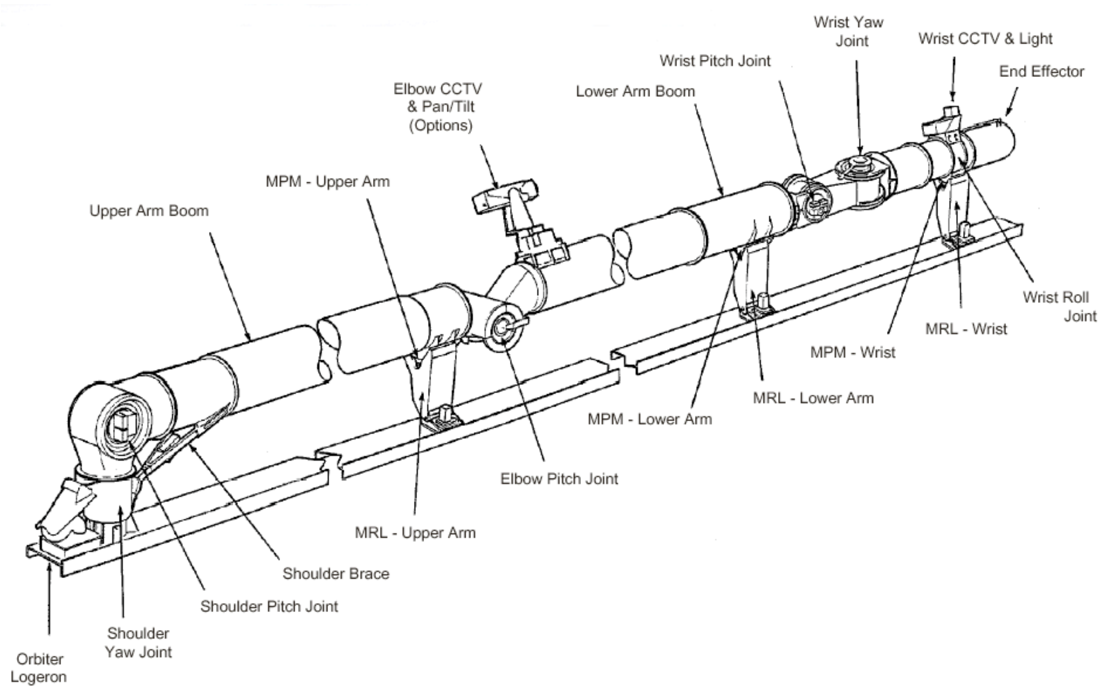

Figure 27. Schematic of SRMS architecture (courtesy M.D. Robotics).

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 $\times$ 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.

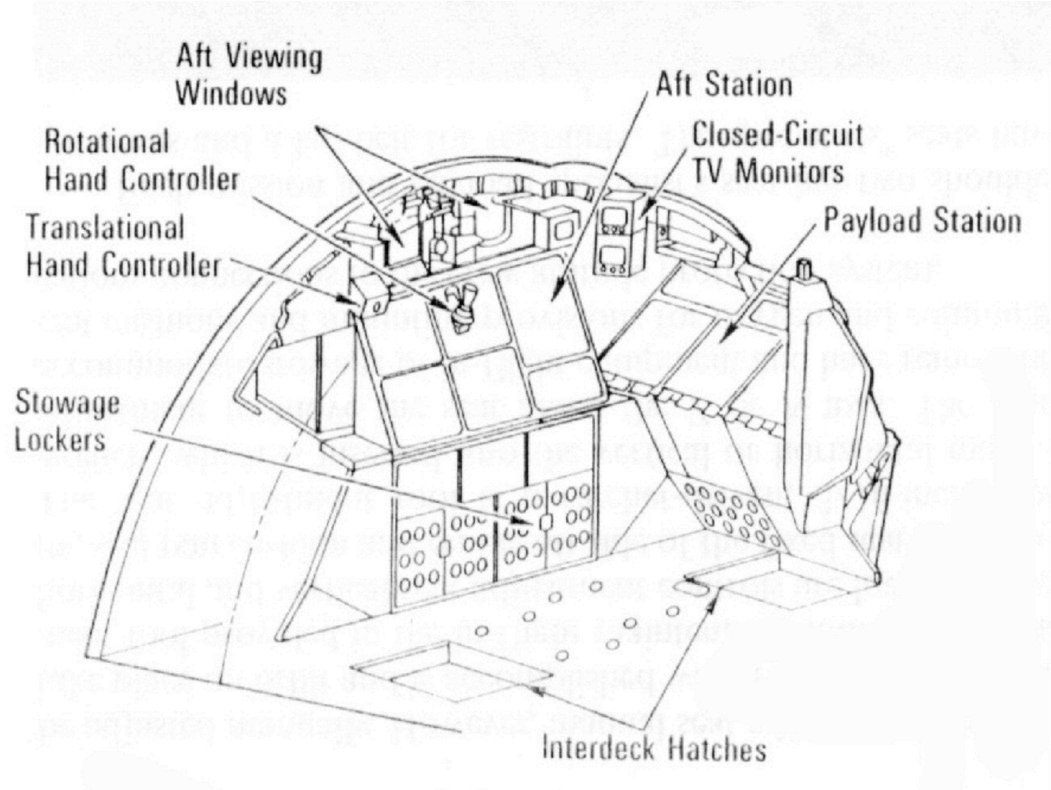

Figure 28. Space shuttle aft flight deck (courtesy NASA).

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 ${}^{n}T$ 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 ${}^{0}T$, ${}^{1}T$ and ${}^{2}T$ together at the shoulder joint, joint 2. Similarly, the axes of joints 5 and 6 are coincident and thus the origins of ${}^{5}T$ and ${}^{6}T$ 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.

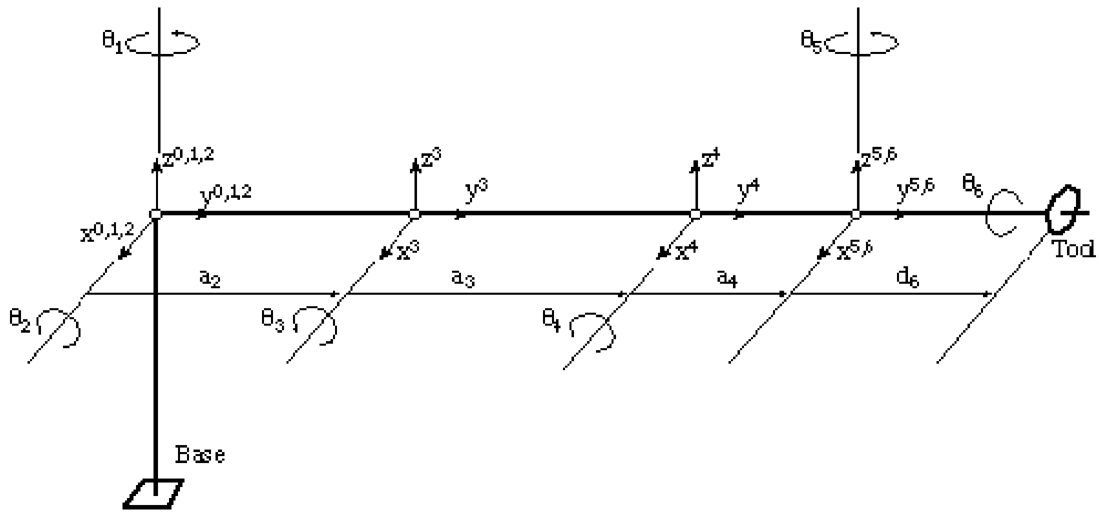

Figure 29. Coordinate reference frames of complete manipulator.

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:

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

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:

$$\theta_4 = \mathrm{atan}\,2\left(-a_2S_3p_u + (a_2C_3 + a_3)p_v, (a_2C_3 + a_3)p_u + a_2S_3p_v\right)$$

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:

$$\theta_5 = \text{atan}\,2\left(-C_1 o_x - S_1 o_y , C_{234}(-S_1 o_x + C_1 o_y) + S_{234} o_z\right)$$
$$\theta_6 = \text{atan}\,2\left(-S_{234}(S_1 n_x - C_1 n_y) - C_{234} n_z , S_{234}(S_1 a_x - C_1 a_y) - C_{234} a_z\right)$$

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).