ORNL/CP-102648

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Submitted to the

American Nuclear Society 8th Topical Meeting on Robotics & Remote Sytsems

25-29 April 1999
Pittsburgh PA

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ABSTRACT

Metaphorically, a teleoperator with master controllers projects the user's arms and hands into a remote area. Therefore, human users interact with teleoperators at a more fundamental level than they do with most human-machine systems. Instead of inputting decisions about how the system should function, teleoperator users input the movements they might make if they were truly in the remote area and the remote machine must recreate their trajectories and impedance. This intense human-machine interaction requires displays and controls more carefully attuned to human motor capabilities than is necessary with most systems.

It is important for teleoperated manipulators to be able to recreate human trajectories and impedance in real time. One method for assessing manipulator performance is to observe how well a system behaves while a human user completes human dexterity tasks with it. Fitts' tapping task has been used many times in the past for this purpose.

This report describes such a performance assessment. The International Submarine Engineering (ISE) Autonomous/Teleoperated Operations Manipulator (ATOM) servomanipulator system was evaluated using a generic positioning accuracy task. The task is a simple one but has the merits of (1) producing a performance function estimate rather than a point estimate and (2) being widely used in the past for human and servomanipulator dexterity tests. Results of testing using this task may, therefore, allow comparison with other manipulators, and is generically representative of a broad class of tasks.

Results of the testing indicate that the ATOM manipulator is capable of performing the task. Force reflection had a negative impact on task efficiency in these data. This was most likely caused by the high resistance to movement the master controller exhibited with the force reflection engaged. Measurements of exerted forces were not made, so it is not possible to say whether the force reflection helped participants control force during testing.

1. Introduction

Metaphorically, a teleoperator with master controllers projects the user's arms and hands into a remote area. Therefore, human users interact with teleoperators at a more fundamental level than they do with most human-machine systems. Instead of inputting decisions about how the system should function, teleoperator users input the movements they might make if they were truly in the remote area and the remote machine must recreate their trajectories and impedance. This intense human-machine interaction requires displays and controls more carefully attuned to human motor capabilities than is necessary with most systems.

One handy way to assess how well a manipulator projects human manipulative capability is by performing tasks used to quantify human dexterity with it. This approach has the advantage of allowing comparison of teleoperator performance to unencumbered (by a teleoperator) human performance. One common task used for this purpose is a target acquisition task, or Fitts' tapping task, as certain members of this class of task are sometimes called. Target acquisition tasks involve rapid movement with an endpoint accuracy requirement. When this type of task is done within completion time regimes that permit visual monitoring of the movement, they follow what is called Fitts' Law, which states:

$$MT = a + b \bullet ID, \tag{1}$$

where MT is the time required to complete the movement, a and b are empirically derived constants for the human linkages involved in the movement, and ID, or *Index of Difficulty*, is calculated as:

$$ID = \log_2\left(\frac{2d}{w}\right), \tag{2}$$

where d is movement distance and w is target diameter. (Very rapid movements like those made by the fingers while typing follow Schmidt's Law; the latter is of little interest in most teleoperator applications.) These equations relate the typical movement time for a task with a given distance and accuracy requirement; the equations may also be used to identify the endpoint accuracy possible, given a distance and desired movement time.

Fitts' Law arises from the organization of the human neuromuscular system. Force impulse production depends upon the number of motor units (a motor unit is a motoneuron and the set of muscle fibers which it activates) participating and the duration of participation (Ulrich and Wing, 1991). Motor units seem to be recruited on the basis of a judgement about the forces needed to accelerate (and then decelerate) the limb towards a target. The greater the required force, the larger the number of motor units recruited. Each motor unit has a characteristic force amplitude; the total force exerted is the sum of motor unit amplitude. However, each motor unit also has noise associated with it. The noise is the result of variability in motor unit impulse amplitude and duration. The noise of an acceleration/deceleration impulse is the sum of motor unit noise. As movement amplitude increases, the number of motor units increases, and the amount of noise increases. Hence, the relationship between movement time on the one hand, and distance and accuracy on the other hand, arises. Wadman et al. (1979) observed data that support this model: they found increased EMG activity duration occurring with increased movement distance during wrist movements.

Judging telemanipulator performance on the basis of target acquisition tasks depends on determining what the constants a and b are for a particular system. This paper describes such a performance assessment. The test was performed on the International Submarine Engineering's (ISE) Autonomous/Teleoperated Operations Manipulator (ATOM). These tests included both a Fitts reciprocal tapping test (Fitts, 1954) and a target tracking test. The Fitts' test was used in order to determine the dexterity of the manipulator when trying to execute a basic touching task.

2. Methods

2.1. Procedures

The tests involved Fitts' reciprocal tapping task. The Fitts task required moving back and forth between two targets on a task board and touching them with a plastic stylus held by the manipulator. The time required to touch both targets 5 times was recorded. ID's of 3, 4, and 5 were used which corresponded to using 2 inch diameter targets with a separation of 8 inches, 2 inch diameter targets with a separation of 16 inches, and 1 inch diameter targets with a separation of 16 inches respectively. The tasks were performed in three different orientations: orthogonal, oblique, and vertical. The orthogonal orientation involved movement perpendicular to the manipulator (i.e., left to right and then back), the oblique orientation involved movement left and in and right and out from the manipulator, and the vertical orientation involved movement in the vertical plane (i.e., up and down).

Each operator performed each of the three different tasks 10 times as a total of 30 trials were performed for each of the three orientations. The ID order was determined randomly and a complete set of all three tasks was completed before any ID value was repeated. The operators were not allowed to perform trials for more than one orientation per day. (Time constraints, however, required two tests per day on two occasions.) The order of task orientation was constant for all nine operators, with the orthogonal orientation first, then the oblique orientation, and finally the vertical orientation. Tests for each orientation were repeated twice: first with force reflection and second without force reflection.

2.2. Participants

A total of nine different operators was used for the Fitts' task. Three of the operators were technicians working at Oak Ridge National Laboratory's (ORNL) Robotics and Process Systems Division. Each was trained and certified as a teleoperator according to ORNL procedure. Despite having extensive experience with other teleoperator systems, the only experience each of the technicians had with the ATOM manipulator was that obtained during the minimal practice time and the actual tests. Three summer interns working at ORNL who had little or no previous experience working with teleoperator systems were also involved in the testing. The other three operators were employees of ORNL who were familiar with teleoperated systems, but were not trained users. None of them had any previous experience with the ATOM manipulator.

2.3. Manipulator

The ATOM is a six degree-of-freedom, hydraulic manipulator. It used UCON WS-34 polyalkylene glycol hydraulic fluid as its hydraulic power unit provided 10hp with a 7.5 gpm flow rate. It had a 300-lb lift capacity with an extended reach of 75 inches. Table 1 details the range of motion and type of actuators found in each of the manipulator joints. The ATOM manipulator was capable of providing force reflection to the operator, with a maximum reflected force of 3 pounds

Table 1. Manipulator characteristics.

Joint	Range of Motion	Actuator
swing	270 deg.	rotary
shoulder	100 deg.	Linear
shoulder	100 deg.	linear
elbow	140 deg.	linear
wrist pitch	180 deg.	Rotary
wrist rotate	360 deg. continuous	rotary
gripper	4 in.	linear

2.4. Experimental Task.

The task was Fitts' reciprocal tapping task [9]; this task was selected because (1) unencumbered human performance of this task has been widely studied and (2) it is representative of serial target acquisitions that occur during manual tasks done with teleoperators. Task sizes were selected to span a representative work envelope. The task apparatus consisted of a piece of 5.08 cm by 10.16 cm lumber, 60.96 cm long, with 4 target position holes. Holes were drilled through each board 10.16, 20.32, 30.48, and 50.80 centimeters from one end to create three target separations: 10.16 cm, 20.32 cm, and 40.64 cm. The targets were circular wooden disks made of 2.54 cm thick plywood and three target diameters were used: 2.54 cm, 5.08 cm, and 10.16 cm. A wooden dowel was attached to the bottom of the targets to allow them to be inserted into the target position holes.

A stylus made from a 12.7 mm diameter, white PVC tube and locked in the grasp of the servomanipulator was used to touch the targets. Participants were instructed move the servomanipulator so that the end of the stylus (i.e., within 6 mm of the tip, a region covered with a single layer of gray duct tape) touched the top surface of the target. There were 3 versions of the tapping task, differing in the master controller motions participants made to move the slave from target to target. In the horizontal orientation, the path from one target to the other was horizontal and perpendicular to the participant's saggital plane: this version required side-to-side master controller and slave arm motion. In the oblique orientation, the path was horizontal and at a 45-degree angle to the saggital plane: this version required a master controller motion away from the participant's body and towards the right-hand side, and then a reciprocal motion towards the body and to the left-hand side. In the vertical orientation, the path from one target to the other was vertical. Different orientations were used to ensure that the data were representative of the multi-joint movements typical of teleoperation. Throughout the Fitts tests, the operators viewed the task board using a video camera and a television monitor in order to simulate remote maintenance.

3. Results

3.1. Regression Equations for MT and ID

One of the benefits of using Fitts' tapping task for manipulator performance evaluation is that it allows calculation of a least-squares regression line that relates task efficiency to task difficulty. This allows a richer comparison of manipulator performance than does comparison based on a single estimate of task performance (like time to complete a single version of a task).

After completion of data collection, least-squares regression lines were calculated for each task orientation and force-reflection condition, for each participant. (Separate regression equations were calculated by participant to keep individual differences from being confounded with the relationship between ID and MT.) Table 2 presents the averages and standard deviations for the slope, intercept, and correlation coefficients. (The correlation coefficient expresses the strength of relationship between two variables and ranges from 1.0 for a perfect positive relationship and -1.0 for a perfect negative relationship.)

From Table 2, all of the average correlation coefficients are within the range from 0.71 to 0.89, evidence of a strong relationship between MT and ID across conditions in these data. The slopes of the regression lines are useful measures of the sensitivity of MT to changes in ID, for comparison across conditions. It seems that ID had a greater impact on MT during completion of the task with force reflection than without force reflection, in all orientations. Performance of the task in the oblique orientation showed the greatest sensitivity of MT to ID in both force reflection conditions. Performance of the task in the vertical orientation showed the least sensitivity with force reflection, but performance in the horizontal orientation showed the least sensitivity without force reflection.

Figure 1 shows lines plotted from the regression equations for each condition combination. From the figure, it appears that the task was easiest in the horizontal orientation without force reflection and most difficult in the oblique orientation with force reflection.

3.2. Orientation and force Reflection

The MT data were submitted to a multi-variate analysis of covariance to determine the statistical reliability of observed differences among conditions, using a general linear model (GLM) approach. Statistics were calculated using the Statistical Analysis System (SAS). The statistical model used each participant's scores as separate criteria and evaluated the impact of ID, task orientation, force reflection, and the interaction of task orientation and force reflection on the entire set of scores. Index of Difficulty was entered as a continuous variable; task orientation was a 3-level factor fully crossed with force reflection, a 2-level factor. The F approximation calculated from Wilks' λ statistic was used for significance tests. Table 3 presents the results of the statistical analysis. All of the effects in the model produced statistically significant differences, with a very strict significance criterion.

Table 2. Averages and standard deviations of intercepts, slopes, and correlation coefficients for each condition combination.

	With Force Reflection						**Without Force Reflection**					
	Intercept		**Slope**		**Correlation Coefficient**		**Intercept**		**Slope**		**Correlation Coefficient**	
Task Orientation	**Avg.**	**StD.**	**Avg.**	**StD.**	**Avg.**	**StD.**	**Avg.**	**StD.**	**Avg.**	**StD.**	**Avg.**	**StD.**
Horizontal	-0.26	0.69	0.61	0.29	0.78	0.08	-0.04	1.17	0.70	0.52	0.71	0.14
Oblique	-0.48	1.33	0.89	0.45	0.84	0.11	-0.41	0.92	0.95	0.35	0.89	0.04
Vertical	0.63	0.85	0.52	0.14	0.74	0.14	0.01	1.32	0.77	0.36	0.78	0.11

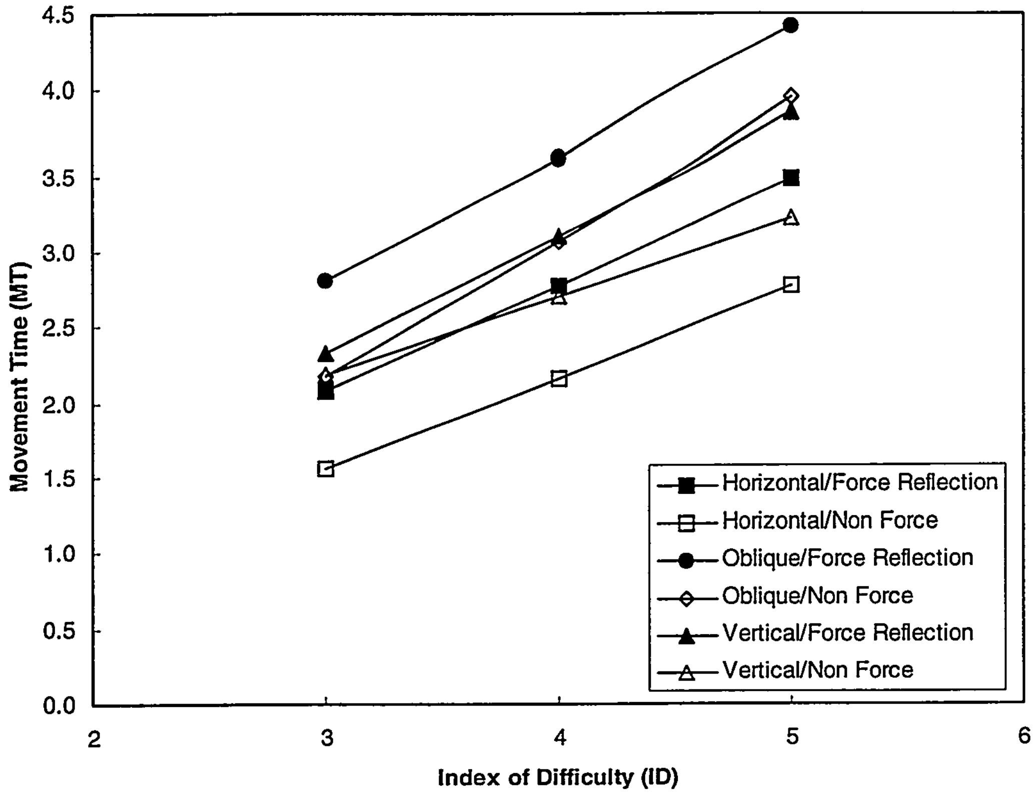

Figure 1. Regression line for each condition combination.

Figure 2 shows the average MT for each task orientation and force reflection combination. From the figure, the source of the significant difference between force reflection conditions seems to stem from a performance efficiency advantage without force reflection. Average MT for all three task orientation conditions was shorter without force reflection than it was with force reflection.

Table 3. Results of the multi-variate analysis of covariance.

Source	*Num. df*	*Den. Df*	*F*	$\alpha \leq$
Index of Difficulty	7	77	96.28	0.0001
Task Orientation	14	154	23.80	0.0001
Force Reflection	7	77	24.30	0.0001
Task Orientation X Force Reflection	14	154	17.60	0.0001

Again from Figure 2, the significant MT difference for task orientation seems to originate in an efficiency ranking that is stable across force reflection conditions. The horizontal orientation required less time than either the vertical or oblique orientations. The oblique orientation required more time to complete than the other orientations.

4. Discussion

4.1. The Impact of Force Reflection

Force reflection is often construed as important, or even necessary, for good remote manipulation. From these data, it appears that, in fact, force reflection retards performance. However, it is important to recognize that it is not possible to completely describe teleoperator performance using a unitary figure of merit. The proper approach is to use multi-measure strategies that best fit the needs of the application under consideration. Understanding criteria helps us understand data and properly interpret it. The history of force reflection research illustrates the importance of carefully planned, multi-measure performance assessment. The data regarding the efficiency of teleoperators alone when force reflection is available (e.g., time to complete tasks) do not consistently demonstrate an advantage for it; however, when the forces generated by the teleoperator in the remote area are measured, it appears that force reflection is usually beneficial.

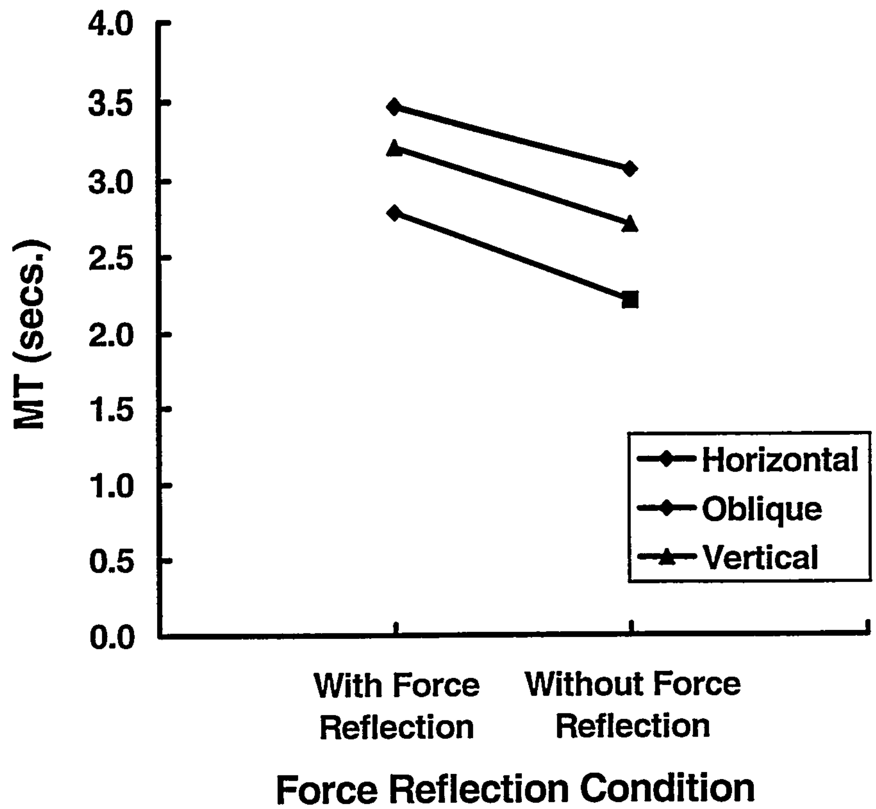

Figure 2. Average MT for each condition combination.

Force reflection probably reduced manipulator efficiency in the current data by increasing resistance to movement. This would have had the effect of requiring greater force amplitude from users, thereby increasing the noise associated with any movement. It may be possible to maintain the effectiveness of force reflection while improving efficiency by scaling down reflected forces. It is possible to maintain the information present in force reflection while reducing resistance to movement, by reflecting a proportion of the remote forces rather than fully recreating forces. For example, it is possible to present 1 unit of force to the user for every 4 units of force exerted remotely. As long as reflected forces are uniformly representative of remote forces, the information content of force reflection is maintained. At the same time, lower reflected forces mean less resistance to movement and more efficient trajectory generation.

4.2. Comparisons with Other Manipulators

Figure 3 presents functions describing the performance of another manipulator on the same target acquisition tasks. The value of using a simple task that produces a figure of merit describing both the efficiency and quality of task completion is that the performance of one manipulator can readily be compared to that of another. ORNL (and others) have collected performance data for other remote manipulator systems using Fitts' task, and so it is possible to place the performance of the ATOM in the context of another manipulator doing the same task. Figure 3 includes performance functions for the ORNL Advance Servomanipulator (ASM) and unencumbered humans, performing the same target acquisition tasks (and using the same task board) as for the ATOM (the ASM and human data are from Draper et al., 1991). In all cases, performance is averaged across orientations. The functions within the

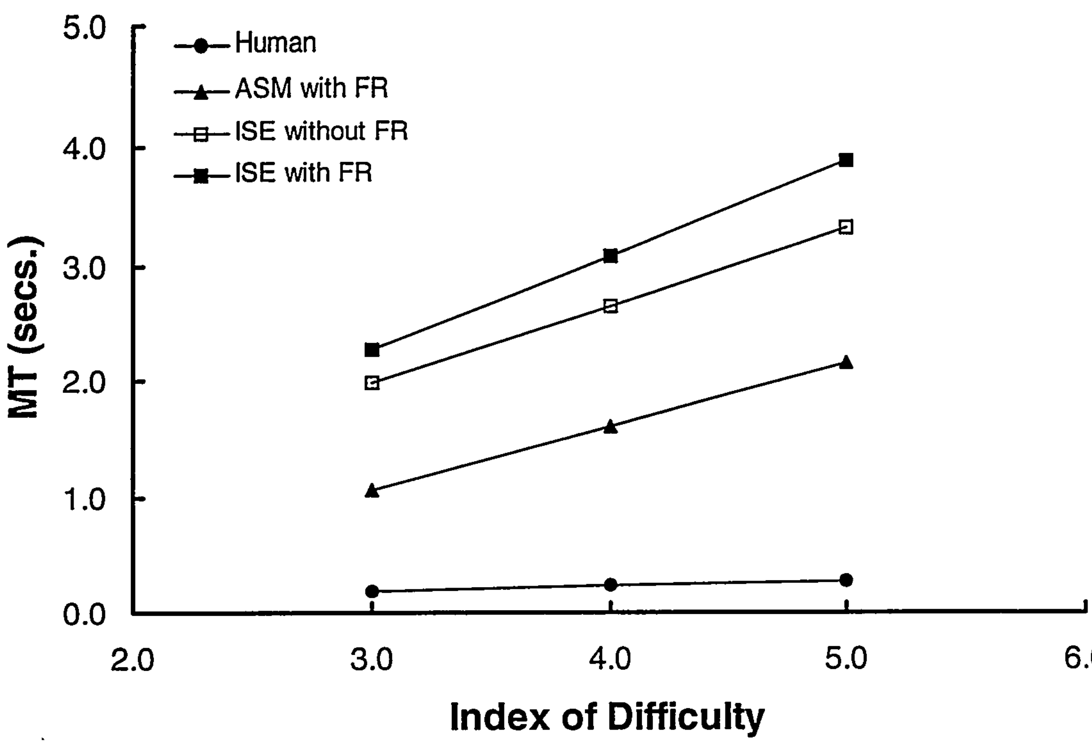

Figure 3. Comparison of ISE performance with the ASM and unencumbered humans.

figure are calculated using empirical parameters identified in preceding research and the ID range used in the current experiment.

4.3. Comments on Fitts' Task

Responsiveness may be defined as the ability of a telerobotic manipulator to recreate human movements and impedance in time and space. From this perspective, Fitts' tapping task is an excellent tool for evaluating the trajectory-generating portion of responsiveness. However, it does not adequately assess the impedance part of responsiveness. A task of this nature may not represent others requiring contact with the remote environment. Variations of the task that involve insertions, hence requiring more contact with the environment, are better at assessing the latter. For examples, see Massimino and Sheridan (1994) or Repperger, Remis, and Merrill (1990). The former used a version of Fitts' task that required insertion of a peg into a hole. In that task, which requires controlling contact with the environment, force reflection enhanced performance. Draper et al. (1987) found that force reflection did not always enhance the efficiency of performance (for representative nuclear industry remote handling tasks) but did allow users to moderate the forces they applied, and may have reduced the number of errors they committed.

Fitts' (1954) adopted an information-theoretic explanation of the relationship between MT and ID. He theorized that human control of rapid, aimed movements was *analogous* to transmission of information in a communication system. This analogy has held up well empirically, but several authors have contested the information theory explanation without necessarily contesting the relationship between MT and ID (notably MacKenzie, 1992). Another perspective contends that the MT and ID relationship is the result of fundamental properties of human movement control. The force that must be generated to make them largely determines the endpoint accuracy of movements. The greater the force, the more muscle fibers that must be involved, and the higher the level of noise inherent in the movement. If this is true it is particularly important for teleoperated manipulators. The implication is that the higher the forces that a user must exert to move a master controller, the lower the accuracy that can be expected of that movement. The data in the present study which show less efficient performance while using force reflection seem to support that argument.

Target acquisition tasks like Fitts' tapping task are probably not used enough in teleoperator evaluations. They lack mundane reality, that is, they don't appear to be related to any real-world tasks to the casual observer. However, teleoperator tasks may be considered as a series of target acquisitions, each requiring planning and executing a three-dimensional trajectory to move the end-effector from a starting point to a target in the remote area. Placing the socket of a wrench on a bolt is a good example. Removing a flange fastened by several bolts requires an inter-related set of these target acquisitions. Therefore, Fitts' task is, in fact, representative of a wide variety of real-world tasks. It has considerable value for assessing the performance of teleoperated manipulators.

ACKNOWLEDGEMENTS

This work was performed at the Oak Ridge National Laboratory, in the Robotics & Process Systems Division. The Oak Ridge National Laboratory is managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract DE-AC05-96OR22464. The opinions expressed are those of the authors, and not necessarily those of Lockheed Martin Energy Research Corp., the Oak Ridge National Laboratory, or the Robotics & Process Systems Division.

REFERENCES

Draper, J. V., Handel, S., Hood, C. C., & Kring, C. T. (1991). Three experiments with stereoscopic television: When it works and why. ***Proceedings of the 1991 IEEE International Conference on Systems, Man., and Cybernetics***. Richmond, VA: Institute of Electrical and Electronics Engineers, 105-110

Draper, J. V., Herndon, J. N., Weil, B. S., & Moore, W. E. (1987). Effects of force reflection on servomanipulator performance., ***Proceedings of the American Nuclear Society International Topical Meeting on Remote Handling and Robotics in Hostile Environments,*** Pasco, WA, 654-660.

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.

MacKenzie, I. S. (1992). Fitt's Law as a research and design tool in human-computer interaction. ***Human-Computer Interaction***, 7, 91-139.

Massimino, M. J. and Sheridan, T. B. (1994). Teleoperator performance with varying force and visual feedback. ***Human Factors***, 36 (1), 145-157.

Repperger, D. W., Remis, S. J., and Merrill, G. (1990). Performance measures of teleoperation using an exoskeleton device. ***Proceedings of the 1990 IEEE International Conference on Robotics and Automation***. Los Alamitos, CA: IEEE Computer Society Press, 552-557.

Ulrich, R. and Wing, A. M. (1991). A recruitment theory of force-time relations in the production of brief force pulses: the parallel force unit model. ***Psychological Review***, 98 (2), 268-294.

Wadman, W. J, Denier van der Gon, J. J., Geuze, R. H., and Mol, C. R. (1979). Control of fast goal-directed arm movements. ***Journal of Human Movement Studies***, 5, 3-17.